

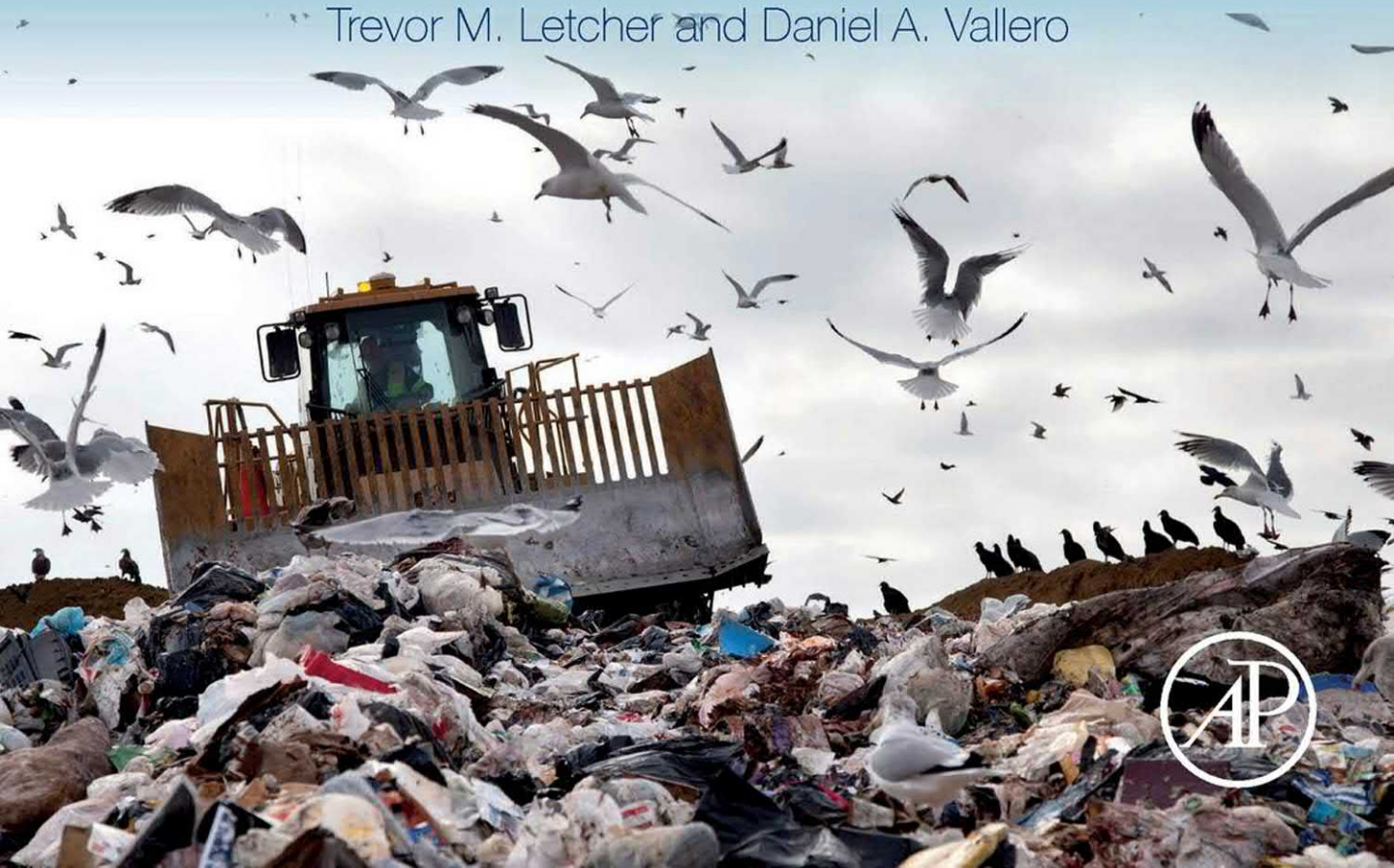
FOR REFERENCE PURPOSES ONLY
SECOND EDITION

WASTE

A Handbook for Management



Edited by
Trevor M. Letcher and Daniel A. Vallero



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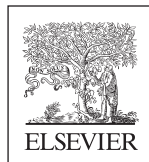
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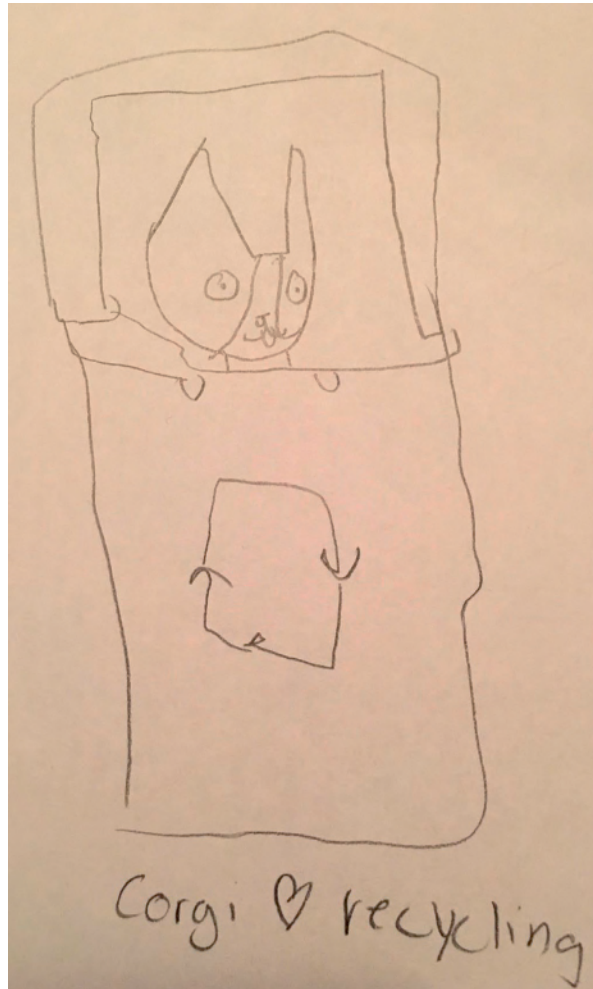
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Dedication

For our wives, children, and grandchildren, as well as the past, present, and future engineers, scientists, managers, and all concerned with the challenge of addressing wastes. Already optimists, editing this second edition has made

us even more confident in the science and management strategies that will underpin success. We welcome the next generation of waste management.



The environmental stewardship ethos begins young. Sketch: "Corgi in Recycling Bin" by Chloe Jayne Randall (age 10); used with permission.

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Marcel Bosling graduated in Computer Science at RWTH Aachen University in 2013. In 2007, he worked as a student researcher, from 2013 as a research assistant at the Department of Processing and Recycling (I.A.R.). In 2018, Bosling successfully completed his dissertation on the topic “Measurement of Particle-Based Characteristics of Secondary Raw Materials by Optical Sensor Systems” at the I.A.R. Since mid-2018, he has been working for Steinert Elektromagnetbau ([Chapter 10](#)).

John Butler is an independent consultant helping small businesses and NGOs to assess the environmental impacts of their operations and plan for more environmentally benign outcomes. His research is primarily in the field of waste management and using life cycle assessment (LCA) to identify more environmentally benign options in the implementation of waste management policies ([Chapter 15](#)).

Tiago Matos de Carvalho is a PhD graduate from Cranfield University (UK) with a research background in the development of complex space systems, with emphasis on On-Orbit Servicing applications. Since 2010, he has been working in the aerospace industry and has research experience as a product development engineer and systems engineer. His research

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Marian Chertow leads the industrial environmental management program as well as the program on solid waste policy at the Yale School of Forestry and Environmental Studies. She has worked in waste management and recycling in the public, private, and not-for-profit sectors and was an early adopter of “industrial ecology,” which offers a systems approach to questions concerning materials, energy, and waste ([Chapter 18](#)).

Stephen C. Cosper is an Environmental Engineer at the U.S. Construction Engineering Research Laboratory in Champaign, IL. He has a B.S. in Civil Engineering from the University of Illinois and an M.S. in Environmental Science from Indiana University. His research areas are in solid waste management, waste to energy, and net zero waste at military installations and contingency bases ([Chapter 29](#)).

Alexander Feil has worked in industry as editor-in-chief and as a technical director. Since 2012, he works as a Senior Engineer at the Department of Processing and Recycling, RWTH Aachen University, Germany ([Chapter 10](#)).

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Kay Johnen studied Waste Management Engineering at RWTH Aachen University; from 2011, he worked as a student researcher at the Department of Processing and Recycling (I.A.R.). In 2016, he successfully completed his master thesis “Influence of ferromagnetic substances on the sorting with eddy-current-separation.” Since 2017, he works as a research assistant at the I.A.R. focusing on metal recycling of fine fractions ([Chapter 10](#)).

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Valerie L. Shulman is the Secretary General of the European Tyre Recycling Association (ETRA). The research she initiated in 1989 formed the nucleus of ETRA which was founded five years later. ETRA has over 250 member companies and organizations in 46 countries, worldwide. She was a contributor to the Basel Convention Guidelines on Used Tyres (1999) and has represented the recycling industries at Waste Policy hearings in the European Parliament. She has participated in numerous research projects, prepared more than 100 articles in scientific and industry journals and authored or co-authored several books on tyre recycling technologies, materials and applications ([Chapter 26](#)).

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Richard C. Thompson is Head of the International Marine Litter Research Unit at the

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Daniel A. Vallero has conducted research, prepared environmental assessments, and advised US legislative and executive branches on environmental issues, including climate change and acid rain and risks posed by chemicals. At Duke University, he teaches courses in optimization, ethics, sustainable design, and green engineering. As an authority on the environmental measurement and modeling, Dr. Vallero has conducted research on systems engineering, environmental modeling, emergency response, and homeland security, notably leading exposure studies in asbestos-contaminated areas and tracer studies in the urban dispersion program in New York City. He is the author of fourteen engineering textbooks—the most recent are *Translating Diverse Environmental Data into Reliable Information: How to Coordinate Evidence from Different Sources* (2017) and *Air Pollution Calculations* (2019) ([Chapter 1–9, 12, 13, 20, 24, 31–36](#)).

Daniel J. Vallero is a professional civil engineer in the City of Durham, North Carolina's Engineering Section of the Public Works Department. He reviews and ensures the adequacy of projects with respect to zoning, site plans, preliminary plats, construction drawings, building permits and final plats, ensuring that a project adheres to road standards, sidewalk, water system, fire protection systems, sanitary sewer system, and stormwater drainage and conveyance systems. He has practiced in both the private and public sectors, focusing on various aspects of land development, including measures to prevent water pollution, control erosion, and ensure effective use of land ([Chapter 32](#)).

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Preface

Waste presents one of the biggest environmental and public health challenges and the largest expenditure for many municipalities. Private enterprises and public agencies continue to improve their approaches, which involve teamwork among numerous jurisdictions, departments within these jurisdictions, and collaborations between public and private entities. Thus, as with the first edition, the second edition of *WASTE: A Handbook for Management* is designed to be a resource for the manager, designer, practitioner, researcher, teacher, and student.

Waste is defined by everyone but not truly and completely understood by anyone. The scientist, engineer, and consumer each define waste correctly, yet differently. The overriding challenge for the authors was to provide some uniformity, yet allow the diversity of the various aspects of waste in this handbook. The tools available to waste managers for scientifically sound, feasible approaches continue to grow in variety and complexity, so a new, entirely updated and expanded edition was in order. Balance is the key to sound environmental science and engineering, so we continue to borrow from all scientific, engineering, and management disciplines, and a few humanities, to arrive at a balanced resource.

Obviously, no single resource can be sufficiently comprehensive on its own in dealing with waste, so each of the chapters is richly annotated and sourced to give the reader ample avenues for further investigation. That said, this handbook begins the search for information to

support waste management. Since all waste approaches must be tailored to the needs of the manager, we identify additional sources in every chapter.

Like other handbooks, the text begins by discussing the scientific, engineering, and technological principles underlying waste streams. These discussions inform the reader of each waste stream's risks, with an eye toward precautionary, reliable, and resilient approaches to reduce these risks. Indeed, we prefer that the wastes never be generated, so we have devoted greater attention in the 2nd edition to systems and translational sciences, especially in approaching wastes from a life cycle perspective.

The text culminates with recommendations and ideas about best practices and proper management of wastes before, during, and after they are generated. We give considerable attention to treatment and cleanup, but *best* management practices involve the reduction and elimination of waste volume in its various forms, sectors, and streams.

This 2nd edition has retained most chapter titles and indeed most of the original authors. Geoff Blight unfortunately passed away in 2013 and one of his chapters on "Landfill" has been updated by Vallero. In some cases, the original authors no longer work in the areas and their chapters have either been deleted or updated by new authors. The original edition had 32 chapters while this edition has 36. The three sections—*Introduction*, *Waste Streams*, and *Best Practice and Management*—have been retained. The *Introductory* section now contains

chapters on “A Systems Approach to Waste Management” and “Waste and Biogeochemical Cycling.” The *Waste Stream* section now includes three chapters addressing “Plastic Waste”; a chapter on “Coal Waste Streams”; and a chapter on “Production Waste from Oil and Gas Exploration.” The final section on *Best Practice and Management* now includes chapters on “Waste Governance,” “Waste Constituent Pathways,” and “Evaluating the Feasibility of Public Projects.”

The editors share many things in common that have added to this project’s gratification. We both love teaching and research. We respect and adhere to the scientific method. We are blessed with a diverse network of colleagues who readily share their expertise, as evidenced by the chapter authors. We consider ourselves pragmatic and strive to apply the sciences to better humankind. We are also quite different in many ways. One is a thermodynamicist and one an engineer. One has resided in Africa and Europe and the other in North America. One leads fellow chemists into previously uncharted areas of global concerns and the other leads (and follows) environmental scientists and engineers into daunting areas of emerging technologies, optimization, ethics, and sustainability.

The chapter authors and editors know well that the waste management community seldom, if ever, has unanimity and rarely consensus on how best to manage any waste given the diversity of settings. Thus the usefulness of this handbook requires attention to the scientific challenge of how to achieve effective and sustainable solutions to one of the most important and dynamic of society’s problems.

We continue to strive to provide a single volume that is:

- a source book for easy consultation and direction in further studies;
- a book that will lead to helpful comparisons among different waste streams, leading to synergistic solutions; and above all,

- a book that helps to build better and more informed society.

This handbook is:

- a textbook for students and lecturers in science, engineering, and environmental studies;
- a guide for researchers, with links and references to the very latest works;
- ready resource for decision-making officials and parliamentarians and leaders in society who need to be aware of the serious problems created by waste;
- an information source for editors and journalists who also need to know the latest issues on waste;
- a risk management guide for captains of industry, technicians, and maintenance personnel who need to be aware of the problems in their areas and related area; and,
- a compendium for all interested parties, even the more casual readers, enhancing their awareness of the enormity of the problems surrounding waste and the myriad ways to address them.

Perhaps the fundamental value of this book, and where it differs from other books of similar theme, is its pragmatic perspective. Each chapter is written by an expert scientist or engineer working in the specific field tapped to address a particular waste challenge. The book highlights the severity of each of the problems and offers the best solutions and recycling processes. In fact, one of the key values of this book is in what it cannot say. Humility is a virtue in life and in waste management. The chapter authors are upfront about uncertainties and areas of need of advancement and future research.

The challenge of any compendium is to achieve a balance in uniformity of style and format with sufficient latitude for chapter authors to cover their subject matter sufficiently. We believe that we have struck this balance. The units and notation are given as more than one

type (e.g., tons and tonnes) when these are not used uniformly by professionals or by scientific disciplines. However, the English language varies for authors, depending on the dialect of the nation where they practice. For example, the reader will note that some authors use “authorize” whereas others use “authorise.” Indeed, the terms are only different in spelling and have identical meanings. We believe this cultural richness and authenticity is more important than internal consistency. After all, as Emerson warned, “a foolish consistency is the hobgoblin of little minds, adored by little statesmen and philosophers and divines.”

Waste in its many forms is among one of the most important issues facing the world today. Our disregard for the problems generated by waste will compromise our children’s and grandchildren’s lives. This does not have to be our generation’s legacy. An honest and scientifically sound appraisal of the stresses that increase with geopolitical change is needed more than ever. For example, the relocation of large sectors of the population to hazard zones, for example, coastlines and river valleys, which exacerbates the problems presented by wastes. We are optimistic, however, since the engineering, technologies, and management tools needed to address these growing challenges continue to improve. This is evident even since the 1st edition, so we have strived to include several in the 2nd. This gives us hope and the expectation that the increasing awareness and

growing stewardship ethos will enhance the likelihood of innovation and successful solutions. It is our hope that our great-grandchildren will read this and wonder what all the fuss was about.

Structure

The book is divided into three parts:

- *Part 1: Introduction to Waste Management* includes a history of waste management, an introduction to systems thinking, life cycle perspectives, green engineering, and sustainable design as related to waste management, waste regulations, and waste collection;
- *Part 2: Waste Streams* is a collection of chapters on the most important waste streams in our society and
- *Part 3: Best Practice and Management* contains chapters on risk management, accountability, communications, and involvement on diverse stakeholders. This section focuses on optimizing waste management for both scientific soundness and economic feasibility, with risk reduction approaches that are reliable and resilient.

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Prologue

Waste has vexed civilization for thousands of years. Most recently, however, waste concerns have grown exponentially with the industrial and petrochemical revolutions, a rapid growth in world population, and greater consumerism. Generally, engineers and scientists have done much to address previous problems long considered intractable (e.g., open dumps, lack of substitutes for dangerous products, and pesticides). Advances in reduction of waste volume and hazards have encouraged a well-deserved dose of technological optimism, although the amount and hazardous nature of wastes continue to threaten society. The waste threat impinges on our public health and the integrity of ecosystems; it can compromise our esthetic sensibilities and it can be economically crippling. Several chapters in this book address this last point which is so crucial yet often ignored in technical handbooks.

Indeed, the economic losses posed by wastes indicate two failings. First, waste is always an indication of inefficiency. Note that every mass and energy balance includes the mass or energy exiting the control volume. The amount and type of mass or energy that exit along the waste streams are examples of inefficiency. Second, any mass or energy exiting along these pathways, which introduces costs for handling and treatment and can be staggering, must be addressed. Thus eliminating or reducing waste helps the “bottom line” in two ways, that is, improving efficiency and avoiding the need for expensive controls.

Over the past few decades, in isolated places, waste and pollution have reached uncomfortable and, all too often, dangerous levels. From

a public health point of view, one need only to think back to indelible human-caused disasters at Chernobyl, Bhopal, Donora, London, and other cities throughout the world. Even, extreme so-called natural events are worsened by human decisions. Human actions can contribute to the likelihood of their occurrence and the severity of damage, such as by building in vulnerable areas. Management decisions can increase the numbers of people who will experience harm, such as the recent natural occurrence of the earthquake and tsunami in the Sea of Japan. The quake resulted from Japan’s tectonic situation, a completely nonhuman cause. The main island, Honshu Island, is located where the Eurasian, Pacific, and Philippine Sea tectonic plates meet and push against each other. The tsunami that occurred was also to be expected, since the first two laws of motion dictate that the release of this seismic energy had to be displaced. The wave is merely the result of energy transport via the waves. The decision to cite a nuclear power plant within a high hazard zone, the lack of preparedness for cooling of fuel rods, the weaknesses in evacuation planning and other planning and engineering failures led to the human and ecological disasters that will continue for decades, at least in terms of unacceptable levels of radioisotopes and other contamination [1].

Such episodes are one of the myriad ways in which wastes pose problems. Waste-related problems have both temporal and spatial aspects. Chernobyl provides an example of the most toxic forms of waste (radioactive carcinogens) being released rapidly (a meltdown that

can be measured in hours) over vast regions of the world. It also demonstrates that the exposures and effects of a rapid release can be quite long lived, where the concentrations of isotopes from the disaster have been measured for years after, and the effects began to be detected almost immediately (acute radiation poisoning) and continue to be diagnosed (leukemia and other forms of cancer). Bhopal demonstrates a large, sudden release of a toxic gas (methyl isocyanate) with immediate and spatially confined exposures but with both short-term (death, blindness, and other acute effects) and long-term effects that are still being diagnosed. The urban episodes did not result from a single emission or release but from a cumulative release of several source types (notably power plants, refineries, steel mills, and vehicles). Open dumps had slowly led to air and water pollution that affected millions of people in developed nations and continue to be a problem in developing nations. Hazardous waste sites often affect much smaller geographic areas but with compounds so toxic they have been banned or heavily controlled worldwide over the past few decades. Indeed, all such wastes need to be managed properly, whether they are very slowly, over years and decades, affecting large areas and populations, or are being released rapidly over a confined area and a small population.

Sometimes wastes that have been “forgotten” and intentionally hidden can suddenly become an urgent problem. Corroding infrastructure of disused mines, mine dumps, and landfill sites that are not properly controlled, wastelands created by oil exploration in Russian Siberia or the Nigerian delta, and very recently the Danube mud spill and BP’s Deepwater Horizon disaster in the Gulf of Mexico and coal ash pit spills are examples of ecological disasters created by waste that in turn converts priceless wetlands, coasts, and other resources into vast wastelands and “no-go” areas of the most appalling kind.

Wastes manifest themselves in surprising new ways, as the BP disaster reminds us.

Although the danger to workers on a rig is always present, the events that led to the explosion seem to have been similar to those in Bhopal. They are both reminders that the confluence of even unlikely events can lead to tragic results. Sometimes, the wastes that lead to problems are long forgotten. Recently, for example, the crew of clam boat encountered military munitions off the coast of Long Island, New York. The crew gathered shells that contained mustard gas (sulfur mustard), blistering a crew member [2]. This event indicates that weapons and other military wastes are present on the ocean floor around the world (United States Department of Defense estimates 17,000 tons of sulfur mustard in US waters alone). In addition to the mustard gas, these wastes include arsenic, cyanide, lewisite, and sarin gas. Interestingly, this is not necessarily a case of “improper disposal,” as many would argue that these were acceptable waste handling practices at the time of disposal. After all, the vast amount of water and perceived inaccessibility made ocean dumping “acceptable.” This changed in 1972 with the passage of the Marine Protection, Research, and Sanctuaries Act, which banned munitions dumping by the United States, but many orphaned waste sites remain.

As if the human health and ecological costs were not enough, as mentioned, the economic cost of cleaning up badly controlled or unmanaged industrial, mining, agricultural, and municipal waste sites has been enormous. Piles, pits, and plumes of waste are not only marks of inefficiency but are also costly to put right. Put in another way, most industrial plants involve the production of entropy and to overcome it, energy has to be expended. Each waste stream has its own unique energy and mass characteristics, each presenting an engineering challenge unique to these conditions.

This handbook can be seen as a map of a journey from exploitation to sustainability. The questions we pose at the beginning of our journey of exploring waste are as follows:

1. How serious is the global waste situation today?
2. What will our global waste situation be in 20 years' time?
3. How should waste be controlled over the next 20 years?

To answer the last two questions, first we need to decide the acceptable level of waste in an advanced society. The range is from zero level waste to doing nothing. As in most situations, the acceptable level will be somewhere between the extremes. It will need to be adapted to the particular product or system. For example, some products may be very close to zero waste (e.g., materials in newly produced automobile being 100% repurposed). Others will need to be optimized toward the level of waste that can be tolerated and managed so that an important societal need can still be met.

The answers to these three questions lie with our expert authors in the following 32 chapters. We will find that controlling waste is a fairly new concept and the constraints and controls placed on waste in our society have increased commensurately as the awareness of severity of the waste problem has heightened. This is a natural result of our expanding technologies over the past century. As always, technology is a two-edged sword. It introduces new wastes (e.g., electronic and chemical wastes) and provides solutions to the problems generated by these wastes (e.g., electronic sensors to detect waste constituents and new chemicals and microbes to clean up waste). This technological give and take is difficult to predict and, very often, we cannot foresee the problems created by waste by a new process and as a result new controls and regulations on waste appear to follow disasters.

The editors and authors have tried to be both bold and humble. We are bold when we are reasonably certain of some aspect of a particular waste or its constituents. We are simultaneously humble in pointing out our uncertainties.

Knowledge about wastes has grown rapidly in recent decades and many gaps in understanding have been closed. Still, much is not known and yet to be learned. Our intent is that this handbook will not only enhance the practice of waste management but also will advance the state of the science which will strengthen communications and collaborations within the waste management community.

ORGANIZATION

The handbook is organized into three sections. Part 1 considers the various ways in which wastes have been and could be addressed, beginning with a brief history. The typical transition of waste management moves from natural systems without controls to regulated and engineered systems to market-based and life cycle approaches.

Part 2 considers the specific waste streams, particularly the nature of the wastes and how they may affect human health and the environment. Note that the waste streams and waste constituents may fall into any of the categories discussed in Part 1. That is, some waste streams and chemical compounds continue to be uncontrolled, some highly regulated, and some products and systems are becoming "greener," for example, designed and based on life cycles.

Part 3 includes discussions of how to address the waste streams discussed in Part 2. These "best practices" are designed to reduce the risks posed by the wastes. These are all based on credible science and an adherence to engineering principles. Some are more precautionary, that is, actions are recommended in the absence of sufficient evidence if the problems caused by certain wastes are likely to be large and irreversible. Others draw from reliable evidence based on sound science. Part 3 should be the beginning of good waste management, because each location, waste stream, and other factors are highly

variable. The waste practitioner is advised to customize the response according to the problem. For example, a highly hazardous waste that is well contained may predominantly draw upon existing designs for such waste systems, but the same waste in a less controlled environment will require additional measures and contingencies.

THE CHALLENGE

As the reader navigates through the handbook, we recommend considering the following questions, which will be revisited in the Epilogue:

1. *How much is known about each waste stream? What is the state of the science?*
2. *What levels of certainty are needed to take actions?*
3. *How do the various professional and scientific disciplines vary in their approaches?*
4. *How should waste decisions be evaluated?*

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Introduction to Waste Management[☆]

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1 INTRODUCTION

Waste is a fleeting and difficult concept. For example, I recall that one of my professors in the 1970s declaration that some Native American cultures have no word for “waste,” since it is an absurd concept. Whether he was linguistically correct is less important than the abiding truth that since every bit of matter or energy has potential value, why would it not be used? Unfortunately, for the past few centuries, as economies grow they proportionately increase the waste

they generate, at least during the early stages of a nation’s development. This has been characterized as a “race to the bottom,” wherein the need to produce energy, jobs, and other economic output overshadows the concern for pollution and waste [1]. This so-called Environmental Kuznets Curve (Fig. 1.1) is actually and hopefully U-shaped function of economic development. That is, economic metrics like income and capital stock grow commensurately with waste generation [4]. However, with time, pollution decreases while the economy continues to grow [5]. Beyond a certain inflection point, environmental improvement surpasses the damage of economic growth, resulting in a more sustainable and cleaner environment [6].

[☆] This chapter is an expansion and update of Chapter 1 from the first edition, authored by Valerie Shulman, European Tyre Recycling Association.

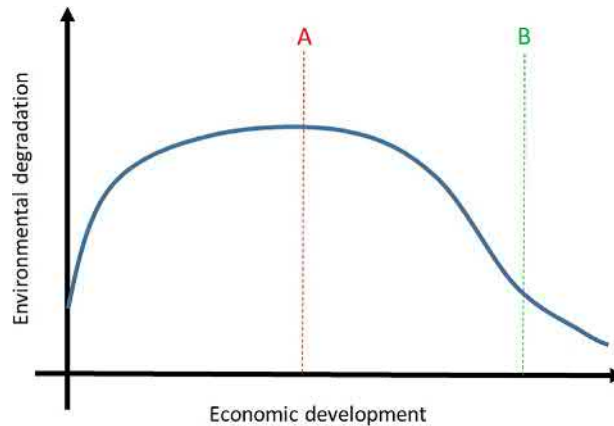


FIG. 1.1 The Environmental Kuznet Curve, which depicts the generalized relationship between a nation's economic development, as indicated by income, capital, and so on, and environmental degradation. Line A represents the inflection point where environmental damage decreases as economic development increases. Note that the curve may not directly relate to waste generation, since it is possible that environmental improvements may occur even as the amount of wastes generated increases, for example, better engineered systems and improved handling [2]. However, at some point (Line B), the nation will see both less environmental damage and less waste generated, that is, waste is recognized as an economic inefficiency and is reduced, that is, the sustainable stage of economic development [3].

Managing wastes is one of society's greatest challenges. However, waste management is among the oldest and most enduring pursuits of human communities around the world—from the earliest civilizations, beginning more than 5000 years ago, until today. In fact, materials have been recycled long before the term was coined in the 20th century. People have always had a knack for seeing value in items cast off by others. Witness the aphorism that “one's trash is another man's treasure.” Indeed, waste management has been inextricably linked with the evolution of human communities, population growth, and the emergence and development of commerce. In the late 20th and early 21st centuries, consumption and production patterns have changed radically due in part to the greater freedom of movement of money, goods, and people.

Population growth has taken precedence in terms of economic development and the creation of waste. World population tripled from approximately two billion in 1925 to 2000 when

it topped six billion. The vast growth spurt has been attributed to the benefits of economic development, including improved health care, higher fertility rates, lower infant mortality, and longer life expectancy. Care must be taken when using such global data. For example, less developed nations have experienced growth without many of these benefits, which means that they continue to experience high infant mortality due to poor nutrition and infectious diseases, whereas wealthier countries have advanced health care, but have witnessed an overall lower fertility rate which endures today.

The population growth has been accompanied by increased material and energy production and consumption, and indirectly, on the accumulation of waste. Some have argued that over time that the single most important driving forces modifying the environment are population size and growth and how man exploits available natural resources. Others, including this writer, hold that the latter is the principal driver and that the earth is not near its carrying

capacity in terms of resources. That is, the usage and exploitation of resources is the principal driver of environmental damage, not the number of people. Indeed, assigning “blame” for population growth has spawned calls for eugenics and rationing (e.g., only the “fit” should be born and fed), which diminishes the value of the individual person [7].

2 THE CATALYST OF CHANGE

At the end of World War II, many nations, especially their urbanized areas in Europe and Asia, were in shambles from virtually every perspective: physically, economically, socially, and environmentally. The War had been the most pervasive military conflict in human history—over land, on the seas, and in the air. Sixty-one countries and many territories on six continents, as well as all of the world’s oceans suffered devastating damage and long-term social, economic, and environmental effects.

Wars are most notorious for their tolls on human populations, but they also severely affect ecosystems. Rivers and lakes, jungles and forests, farmlands and deltas were obliterated with dangerous wastes left behind. Hundreds of cities were demolished and many others rendered virtually uninhabitable. Infrastructure was decimated—bridges, roads, railroads were laid to waste—and rendered nonfunctional.

Almost sixty million civilians and military personnel were killed and tens of millions more were seriously injured and/or permanently maimed. War-induced famines took the lives of over two million more in Africa and Asia [8]. Millions remained homeless throughout the war-torn world. Thousands more were captives of foreign nations—even at home.

According to the International Registry of Sunken Ships, over 12,500 sunken vessels including battleships, aircraft carriers, destroyers, landing craft and over 5000 merchant ships were scattered on ocean floors [9]. Governments

estimate that more than 335,000 aircraft were lost, primarily over Europe, Asia, and Africa [10, 11]. Thousands of tonnes of exploded ordnance including mines, bombs, and various forms of ammunition litter seabeds, fields, jungles, caves, and even home gardens.

More than 60 years after the end of the war, experts estimate that it could take another 150 years to clear the detritus and neutralize the hazardous content which continue to pose dire threats to the environment, humans, and creatures in the seas, on land, and in the air. In addition to military debris, every type of waste imaginable—from natural as well as synthetic materials—including construction rubble, plastic debris, synthetic rubber, electronic equipment and parts, transistors, microwave materials, synthetic fuels, among hundreds of others became the residue of the War and had to be treated and disposed.

Many of the products created for the “war effort” have become the most common products of today, with the same problems and issues surrounding their treatment and disposal. Pesticide formulations, such as the organophosphates, owe their basic chemical structures to chemical war agents. Petrochemical products also have grown substantially in response to war efforts. In addition, abandoned ammunition dumps, practice ranges, and other military facilities continue to be vexing hazardous waste sites.

The definition of wartime waste is complex. For example, among the most harmful and tragic wastes are abandoned land mines, which continue to cause death and inflict harm long after their initial use.

3 SUSTAINABLE DEVELOPMENT: THE CONTEXT FOR RECYCLING

As early as 1942, signatories to the Atlantic Charter had initiated discussions about an organization that could replace the failed League of

Nations. Before the final guns were silenced, world leaders had begun to prepare for the future—one without war, in which disputes could potentially be resolved through discussion and cooperation. The structure and substance of the United Nations was agreed among 50 nations with 51 available to sign it into international law.

Signed on June 26, 1945, the United Nations Charter came into force on October 24, 1945, as an international organization with the goal of providing a platform for dialog and cooperation among nations in order “to save succeeding generations from the scourge of war.” Inherent within the Charter is the recognition that equal rights and self-determination are imperative for each sovereign nation—large or small, wealthy or poor, and must be supported. During the next half-century, these concepts would pervade all aspects of UN undertakings—from decolonization and economic development to environmental and waste issues.

At its inception, five interactive themes were identified: international law and security, economic development and social progress, and human rights. The infrastructure provided for six principal organs: The Trusteeship Council, the Security Council, the General Assembly, the Economic and Social Council, the International Court of Justice, and the Secretariat (see Fig. 1.2). Each organ had its own mission and objectives, which have evolved over time to reflect current issues and needs. The reader will note that the Trusteeship Council is no longer active. It served as a bridge between the now-defunct League of Nations and the United Nations.

Actions related to the environment, and by extension to waste management, can best be described in terms of three broad periods: the postwar period 1945–70; globalization, scientific and environmental awareness 1970–90; implementation and progress 1990 to the present.

3.1 The Postwar Period

The postwar period can be described as one of far-reaching political, social, and economic change.

- Governments were responsible for assessing the war damage and initiating the cleanup and reconstruction of needed infrastructure, homes, civil institutions, business, and industry.
- The OECD was formed in 1960 with 20 members, as an independent forum for industrialized democracies to study and formulate economic and social strategies which could involve developing nations. Today, 31 member countries focus on environmental, economic, and social issues in order to institutionalize and integrate sustainable development concepts into national policy and strategies. Its projects are diverse, ranging from sustainable materials management to corporate responsibility and climate change.
- By mid-1961, almost 750 million people had exercised their right to self-determination and more than 80 once-colonized territories had gained independence, including those under the Trusteeship Council.
- By the end of 1961, a Special Committee on Decolonization was formed to aid 16 non-Trusteeship countries seeking sovereignty.
- With self-determination came new responsibilities and social commitments requiring interactions between wealthier and poorer nations (often described as “north” and “south”). Self-determination became increasingly important as developing countries sought a stronger role in global economics.
- UNCTAD was formed in 1964 as a permanent body of the UN dealing with trade, investment, and development issues. It supports the integration of developing countries into the world economy ensuring

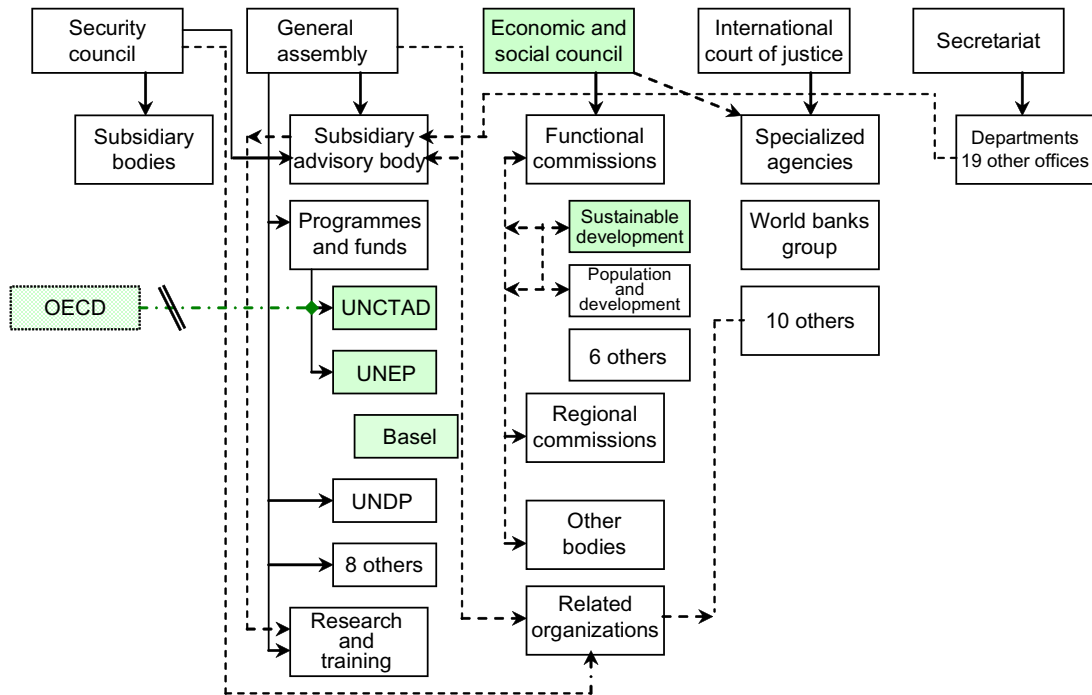


FIG. 1.2 United Nations Structure concerning the environment is an adaptation of the UN organization chart to illustrate the relationships between and among the five current organs. Reprinted with permission from United Nations, *History of the United Nations*. <http://www.un.org/en/sections/history/history-united-nations/index.html>, © United Nations.

domestic policy and international action toward sustainable development do not clash. It helps to assess the needs of the least developed countries in trade relationships, for example, north vs. south and producers vs. consumers.

The 25-year postwar period focused on cleanup and rehabilitation of affected areas. Vast quantities of wastes were collected and often shipped from wealthier to poorer nations for disposal. The concept of self-determination came into play and by the end of the period, poorer nations began to refuse acceptance of external wastes.

An infrastructure for debate had been created with the formation of OECD and UNCTAD. A principal outcome was the establishment of a system of organizations that had the capacity

to act in unison to establish a worldwide mechanism to attain peace, as well as economic and social stability. There was a keen awareness of the relationships between policy, trade, economic development, and environmental impacts.

3.2 The Period of Globalization

The period of globalization and of scientific and environmental awareness, can be described as one of rapid scientific and technological innovation, coinciding with the creation of the UNEP and the Basel Convention. Commercial globalization exacerbated many environmental problems and highlighted the need for global solutions. Together, these bodies have assisted poorer nations to become a driving force in world economic development.

- UNEP was formed in 1972 to smooth a path for international agreements, with the mission of assisting poorer countries to develop and implement environmentally sound policies and practices, coordinate the development of environmental policy consensus, and keep environmental impacts under review. As awareness of cross-border pollution grew, nations worked out agreements with neighboring states. Starting and worked out a series of treaties, conventions, and protocols for controlling pollution and similar problems that crossed national boundaries. International environment conventions promoting science and information drew great support and helped these nations to work in conjunction with policy, guidelines, and treaties on international trade—particularly in terms of hazardous materials—transboundary air pollution, contamination of waterways, among others.
- The Basel Convention created in 1989 under UNEP filled the gap between existing mandates which facilitate and monitor world trade on the one hand, and those which are concerned with sound environmental practices, on the other. The mission of the Basel Convention is to monitor the transboundary movements and management of wastes to ensure their environmentally sound treatment and disposal and to provide support to governments by assisting them to carry out national sustainable objectives.

During the next 20 years these organizations undertook an exhaustive awareness campaign to draw the support of national and local governments, nongovernment organizations, industry, and the public at large. Transboundary movements of wastes required the implementation of environmental management systems to evaluate the quantity and impact of emissions within the environment. New economically-based guidelines were created for the import/export

of wastes for recovery with OECD and Basel support. The guidelines were designed to increase the prevention and minimization of wastes by addressing previous failures and the barriers that have led to low rates of waste reduction.

4 IMPLEMENTATION AND PROGRESS

During the final years of the 20th Century, it became apparent that the unbridled economic growth of the past could not be sustained in future without irreparable damage to the environment. Discussions initiated during the 1960s culminated in a proposal for change at the global level.

The Stockholm meeting of the United Nations Conference on Environment and Development (UNCED) in June 1992 is often marked as the critical turning point in the move toward more sustainable growth practices. It signaled a break from the past and the beginning of a new era.

The goals of the conference were limited. They were first to introduce the concepts and practices inherent in sustainability and second, to provoke sufficient concern and interest for world leaders to make a commitment to delink economic growth from negative environmental impacts.

Simply stated, sustainability requires policies and actions that foster economic and social growth which meet current needs without detriment to the environment. The aim is to not compromise the ability of future generations to meet their needs.

“Environment” was defined in the broadest sense to include all of the conditions, circumstances, and/or influences affecting development. The specific issue was the improved management and use of natural resources, concentrating on the prevention and control of pollution and waste.

Delegates adopted the principle and accepted the challenge of implementing the sustainable

BOX 1.1

INTERNATIONAL BODIES CONCERNED WITH WASTE

United Nations Conference on Environment and Development (UNCED) formulates strategies and actions to stop and reverse the effects of environmental degradation and promote sustainable, environmentally sound development in all countries.

United Nations Conference on Trade and Development (UNCTAD) promotes trade between countries with different social and economic systems and provides a center for harmonizing the trade and development policies of governments and economic groupings.

Organization for Economic Cooperation and Development (OECD) is a permanent body under the UN Conference on Trade and Development (UNCTAD). It was created to assist in removing restrictions and facilitating trade between and among member and nonmember

countries, ensuring that the substances, materials, products, and so on, involved do not pose a threat to the environment or humanity in the receiving country.

UN Environment Programme (UNEP) is the designated authority on environmental issues at the global and regional levels. It was created to coordinate the development of environmental policy consensus and bringing emerging issues to the international community for action.

Basel Convention, under the UN Environment Programme, is specifically concerned with the control of transboundary movements of hazardous and other wastes and their disposal, from OECD countries to non-OECD countries. Further, it is concerned with the identification of those products and materials which could cause damage to the receiving country(ies).

model of development for the 21st Century. One of the most immediate results of the meeting was the creation of the United Nations Environment Programme (UNEP) as the global authority on environmental issues. It was envisioned that the UNEP would smooth the way for international agreements including those between the wealthier northern and poorer southern countries.

The global economic and social nature of the plan led to the involvement of other organizations within the United Nations infrastructure. Described in [Box 1.1](#), these bodies provide the international framework within which intra- and inter-national trade occur, including the movement of wastes.

By the 1992 UNCED meeting in Rio de Janeiro, much of the groundwork had been completed. The infrastructures for both encompassing legislation and actions were in place.

The goal of the conference was to propose alternative strategies and actions that could be undertaken in the short, medium, and long term in order to ensure that consideration and respect for the environment would be integrated into every aspect of the development process. The Basel Convention provided the common framework for the classification, management, and treatment of waste. Briefly, waste was defined as:

...substances or objects which are disposed of or intended to be disposed of or are required to be disposed of by the provisions under national law [12].

Both the Basel Convention and the OECD independently prepared catalogues of the substances, objects, materials, etc., that are defined as waste and separated out those defined as hazardous or dangerous. A final list contains those wastes that are not perceived to pose a risk to the environment or human health. However, it is important to note that the lists are not mutually exclusive and that under certain

conditions, a 'waste' can and often does appear on more than one list. Virtually every conceivable material, product or residue is listed – those that are not specifically named fall under the rubric 'other'.

The definition and annexes served as a guide for transboundary movements of waste, principally for their environmentally sound management. Examples of recovery and disposal operations were appended. Environmentally sound management was broadly defined as:

...taking all practicable steps to ensure that waste is managed in a manner that will protect human health and the environment against adverse effects which may result from such waste [12].

Within the context of the definitions of waste and its environmentally sound recovery and disposal, the OECD laid down the provisions for its transboundary movement and acceptance, within and outside of the member countries. Each country was invited to prepare a list of those wastes that it would no longer accept for either recovery or disposal, due to lack of appropriate treatment facilities, risks to human health, among other reasons. Thus, procedures were also set-out for the non-acceptance of wastes and their return, should they be delivered in error.

Once the framework was established, various tools were examined to assess their capacity for targeting potential environmental impacts. Life cycle analysis was selected as the most appropriate and effective tool for determining the points at which the greatest environmental impacts occur, thus making possible the suggestion and selection of less damaging options. For example, the approach permitted the evaluation of industrial outputs from the production or extraction of raw materials through the design and manufacture of materials and products, as well as during product use.

The definitions, annexes, and provisions were accepted by the delegates. However, many of the participating countries also adopted the provisions to comply with national policy and priorities.

The most hazardous wastes and the most prevalent sources of pollution were targeted

for immediate attention. Five priority waste streams were distinguished. In addition to the more general category of "household waste," postconsumer tires, demolition waste, used cars, halogenated solvents, and hospital waste were earmarked for action.

5 INTERPRETATIONS

Virtually every industry has come under scrutiny from mining to manufacturing and health care. A raft of legislation has been enacted, with the agreement and cooperation of the partners. A horizontal framework was established for waste management including definitions and principles. Treatment operations were defined vertically to include the control of landfill, incineration, and so on. A body of standards is currently being prepared for treatment operations through the International Standards Organization, with support from national standards bodies.

During the 50 years since the initiation of the first discussions on sustainable development in the 1960s, legislation and actions have been put in place to ensure that governments work together with industry and the public at large. Today, the majority, if not all, UN member countries have enacted basic environment and waste management legislation.

Reuse and recycling are again being integrated into industrial activities. However, as they are interpreted today, the concepts of reuse and recycling are inextricably linked to the production and management of waste and by extension, to its prevention and minimization.

Reuse and Recycling have evolved into two of the four pillars which support improved resource management through the prevention of waste and the reuse, recycling and recovery of the wastes that do occur in order to achieve sustainable development goals by reducing reliance on natural resources.

6 THE EXTENT OF THE PROBLEM

Most of this book considers incidents, cases, and subject matter that are generally well documented insofar as the scientific community reaching a consensus that they have caused harm. The awareness of waste management issues has helped to drive environmental policy throughout the world. Even a cursory review of popular sentiment, however, shows that like other environmental and economic problems, waste management decisions never are reached unanimously and seldom enjoy strong consensus. We live a highly polarized world, where science can be “cherry-picked” and “weaponized” to meet some political end. For example, the physics of the greenhouse effect or radioactive decay are seldom questions, but any hypotheses linking anthropogenic activities to changes in global climate and the threats posed by long-term storage of radioactive wastes (and the whole issue of using fission to produce electricity, for that matter) are examples of major disagreements between policy makers, journalists, and lay people, as well as within the scientific research community [13].

This book considers many forms and pathways of wastes from scientific, engineering, and management perspectives. Often, scientific consensus does not exist. Indeed, with advancement of knowledge, we must be open to the possibility that even our closely held waste management paradigms with time will be found to lack the scientific underpinning we had long thought them to have. For example, municipal solid waste (MSW), that is, the trash or garbage collected by towns, cities, and counties, is made up of commonly used and disposed of items like lawn waste and grass clippings, boxes, plastics and other packaging, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. In 2012 US residents, businesses, and institutions generated about 230×10^6 t, where t refers to metric tonne (254 million US tons) of trash and recycled and composted about

79×10^6 t (87 million US tons) of this material, equivalent to a 34.3% recycling rate. On average, we recycled and composted 0.68 kg (1.51 pounds) of our individual waste generation of 2.0 kg per person per day (4.40 pounds per person per day) [14]. As shown in Fig. 1.3, MSW generation rates continued to rise in the 20th century, before leveling off at the beginning of this century [15].

Worldwide, in recent decades, waste management has been a local concern, with local authorities implementing various management practices to stem the burgeoning amounts of solid waste being generated and needing disposal. These measures have included source reduction, recycling, and composting, prevention or diversion of materials from the waste stream. Source reduction involves altering the design, manufacture, or use of products and materials to reduce the amount and toxicity of what gets thrown away. Recycling averts items from reaching the landfill or incinerator. Such items include paper, glass, plastic, and metals. These materials are sorted, collected, and processed and then manufactured, sold, and bought as new products. Composting, the microbial decomposition of the organic fraction of wastes, for example, food and yard trimmings, is an important recycling process; the microbes, mainly bacteria and fungi, produce a substance that is valuable as a soil conditioner and fertilizer, which can be sold or given away by local authorities [13].

What waste remains is the domain of engineering. Engineered landfills, for example, are not only seen as storage facilities, but as waste treatment technologies, that is, the microbial populations must be engineered to enhance the microbial populations to break down the wastes. Unfortunately, if not engineered and managed properly, landfills can also become sources of contamination. Thus they usually have liner systems and other safeguards to prevent contaminants from reaching groundwater. Combusting solid waste is another practice that

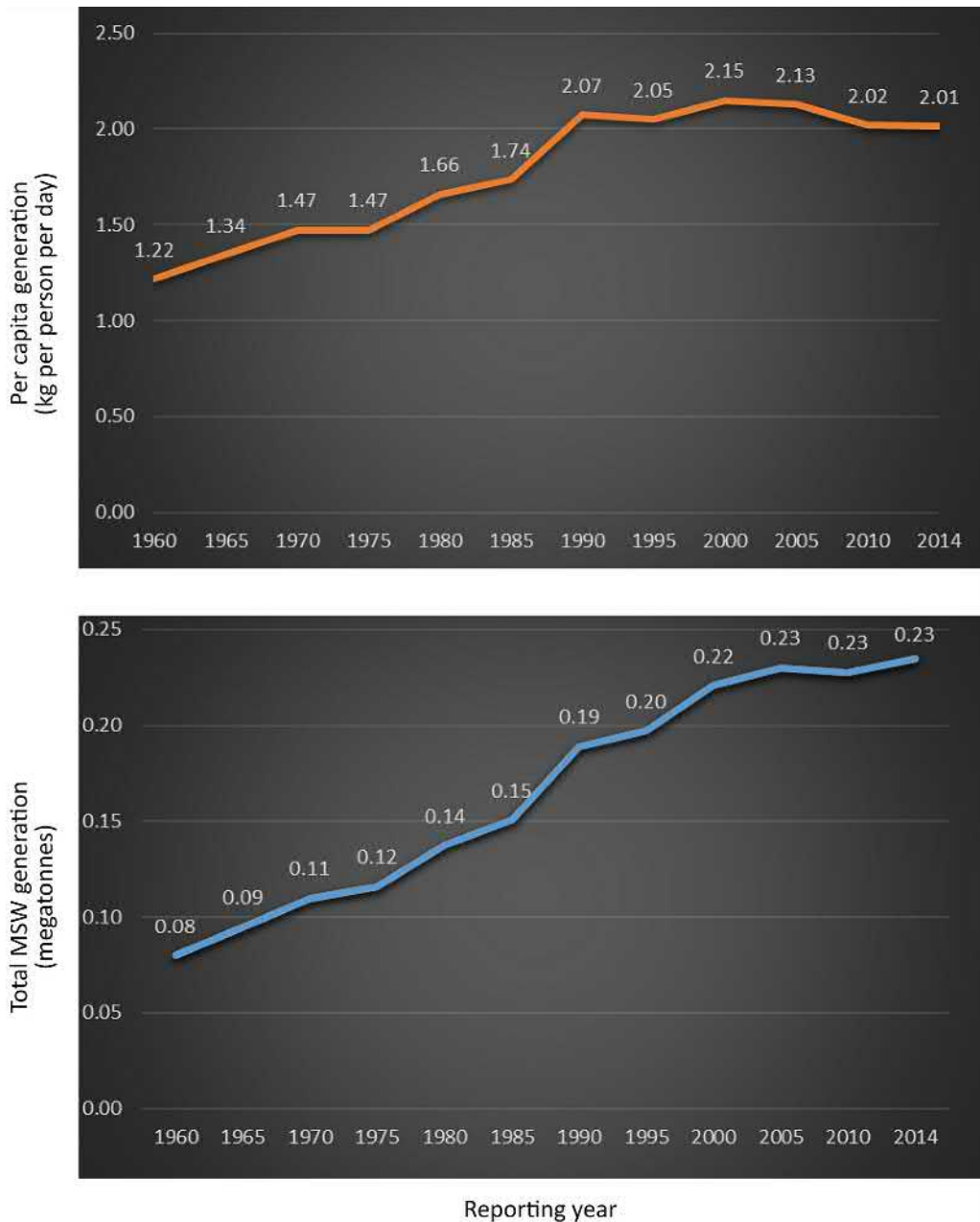


FIG. 1.3 Municipal solid waste generated in the United States. Top: Per capita waste generation rate. Bottom: Total mass generated. From U.S. Environmental Protection Agency, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012*, Solid Waste and Emergency Response, Washington, DC, 2013; U.S. Environmental Protection Agency, *Advancing Sustainable Materials Management: 2014 Fact Sheet*, 2016.

has helped reduce the amount of landfill space needed. Combustion facilities burn solid wastes at high temperatures, reducing waste volume and generating electricity.

That said, how worrisome is the waste management challenge? Is it really a “crisis” as we often hear? Talk show hosts and a recent Home Box Office show hosted by the comedy team, Penn and Teller, consider the solid waste problem to be a convenient myth. One of their postulations is that the issue is another way that the government interferes with privacy and freedoms. In fact, one of Penn and Teller’s conclusions is that the recycling is okay, but the ends should not justify the means. They argue that it is unethical to control people’s life based on a flawed premise.

Most agree that waste management is a necessary endeavor. The public debate often stems around the extent of the problem and the urgency needed to address it. Often, the perception is that greater development threatens environmental quality; more cars, more consumerism, more waste, and more releases of toxicants, but the Kuznet curve argues against this generalization. J.M. Hollander [16] supports the mutualism between economic development, environmental quality, and societal improvements:

People living in poverty perceive the environment very differently from the affluent. To the world’s poor—several billion people—the principal environmental problems are local, not global. They are not the stuff of media headlines or complicated scientific theories. They are mundane, pervasive and painfully obvious:

- Hunger—chronic undernourishment of a billion children and adults caused not only by scarcity of food resources but by poverty, war, and government tyranny and incompetence.
- Contaminated water supplies—a major cause of chronic disease and mortality in the third world.

- Diseases—rampant in the poorest countries. Most could be readily eradicated by modern medicine, while others, including the AIDS epidemic in Africa, could be mitigated by effective public health programs and drug treatments available to the affluent.
- Scarcity—insufficient local supplies of fuelwood and other resources, owing not to intrinsic scarcity but to generations of overexploitation and underreplenishment as part of the constant struggle for survival.
- Lack of education and social inequality, especially of women—lack of education resulting in high birthrates and increasing the difficulty for families to escape from the dungeons of poverty.

Hollander supports his argument with the island of Hispaniola. On the Dominican Republic side, there is much lush vegetation. But, on the Haiti side, the land is denuded. The Dominican Republic has embraced a more open, capitalistic marketplace, while Haiti has suffered the ravages of totalitarian regimes.

Perhaps, this should cause those of us who advocate waste reduction and sustainable solutions to environmental problems to avoid being dismissive of those who do not share our view. It is doubtful they do not agree with our premise that less waste is better, but may disagree with how we address the problem and, ultimately, the trade-offs involved. It is the responsibility of the engineer and manager to offer waste management actions that are scientifically sound, yet feasible.

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A Systems Approach to Waste Management

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1 INTRODUCTION

For most of the 20th Century, wastes were viewed predominately as inevitable by-products of modern times. Waste generation was a necessary reality associated with economic development. Thus addressing wastes was often a matter of reacting to problems as they arise individually in a situationally dependent way. However, the processes that lead to waste can be viewed much more proactively and systematically. It is best to prevent the generation of wastes in the first place. We begin this book with

this latter perspective. That is, waste streams should not only be rendered less toxic and reusable, but wherever possible, completely avoided. Engineers and other waste managers have begun to embrace waste minimization, pollution prevention, and other systematic approach, albeit incrementally. After all these professionals are generally quite practical, so the shift to a “no-waste” paradigm has been a thoughtful one. This book strives to balance the optimism that someday many of the chapters in this book will be eliminated with the practicality that even with waste elimination, recycling, and pollution

prevention, there will still be vast waste management challenges in the decades to come.

2 SYSTEMS VIEW

One challenge for waste management is that environmental problems are commonly addressed in medium-specific ways. In fact, this compartmental approach denies the reality that any environmental problem involves numerous media and solving a problem in one medium, for example, groundwater or soil, can exacerbate problems in another, for example, air. This means that a systems approach to waste management is needed. This means that to approach the very definition of “waste” must be multimedia and multicompartamental. The systems approach requires attention to groundwater, surface water, soil, air, and biota in a wide range of spatial and temporal scales. Waste management must deploy trusted approaches, but open to merging, adapting, and supplanting them with emerging methods. This requires the application and development of reliable ways of measuring and modeling waste-related pollution, in all physical phases, including aerosols, vapors, and gases.

Building a waste management knowledge-base requires an encompassing view that cuts across intellectual boundaries. Integrating environmental, economic, and social aspects of wastes calls for a comprehensive, life cycle perspective.

Systems thinking and attention to the entire life cycle of a substance are of growing interest in environmental research and practice worldwide. Witness the EU’s focus on “downstream users” of products containing chemicals of concern, recent research in ways to improve predictions of chemical exposures and risks in near-field scenarios, and the US Environmental Protection Agency’s recent research in enhancing human exposure information in life cycle analyses’ characterization factors [1]. Sound

waste management considers the entire life cycle of processes, from manufacturing to post-use (e.g., pharmaceuticals that reach receiving waters), all the way to the end-of-product life, for example, recycling and reuse, as well as ways to prevent damage from wastes before they are formed by choosing safer substitutes to chemicals and substituting materials and processes that produce less toxic wastes and that reduce the volume of wastes generated. Scientists and engineers are increasingly applying the lessons of green chemistry and engineering. These include preventing pollution through the design for environment (DfE) and design for disassembly (DfD) [2].

3 PARADIGM EVOLUTION

Green design and sustainable waste management begins with scientific principles to develop objective-oriented, function-based processes. Every element of the life cycle of a product or of a process must mutually benefit the client, the public, and the environment. Waste products can decrease in volume and mass as green designs replace traditional methods of manufacturing, use, and disposal.

One of the key challenges to the systems approach is the entrenchment of product and system design mind-sets that have relied on schemes steeped in an exploitation rather than compatibility with nature. Designs of much of the past four centuries have assumed an almost inexhaustible supply of resources. Such inertia has been and will continue to be difficult to overcome.

Wastes must be managed (and, ideally, avoided) by means of applying the laws of science. The better these principles are understood by the designer, the more likely that the products demanded by society can be produced and used predictably and sustainably. Strategic use of physical science laws must inform designs and engineering decisions.

3.1 New Thinking

New and emerging problems demand new approaches and ways of thinking. As evidence, Albert Einstein has noted:

The significant problems we face cannot be solved at the same level of thinking we were at when we created them [3].

Waste management needs engineered systems, such as landfills, incinerators, infrastructure, and other “built forms.” However, these are only part of a comprehensive response that addresses the totality of matter and energy, with an eye toward ways to reduce “leakage” from the system. McDonough and Braungart captured quite well the need to shift the waste paradigm:

For the engineer that has always taken—indeed has been trained his or her entire life to take—a traditional, linear, cradle to grave approach, focusing on “one-size fits-all” tools and systems, and who expects to use materials and chemicals and energy as he or she has always done, the shift to new models and more diverse input can be unsettling.

In this “cradle-to-cradle” paradigm, waste management begins long before any waste is generated. The function drives the product, so the product is to be considered with respect to its potential life cycles. Such a viewpoint challenges “single-purpose” thinking. For example, a detergent may be redesigned to be “phosphate free,” so that it does not contain one of the nutrients that can lead to eutrophication of lakes, but this does not necessarily translate directly into an ecologically acceptable product if its life cycle includes steps that are harmful.

The phosphate waste is eliminated. However, the life cycle view does not allow the product designer to be satisfied completely with this simple substitution. The approach requires considerations of downstream and upstream effects from an action, even those like the one before that seem to be environmentally sound. For

example, could the substitute ingredient be extracted and translocated by plant life in a way that damages sensitive habitats; makes use of and releases toxic materials in manufacture or use of the detergent; or entails persistent chemical by-products that remain hazardous in storage, treatment, and disposal?

Examples are plentiful of substitutes wreaking even greater havoc than the products they replace. DDT was replaced by the toxic pesticides, aldrin and dieldrin. Substituting incineration for landfills can lead to the release of certain pollutants, for example, dioxins and heavy metals, in far more toxic forms than would be found in the landfill leachate.

Even substitutions that enjoy a consensus of acceptability can be associated with problems. For example, most would agree that replacing organic solvents, like petroleum distillates, with water soluble constituents in automobile paint has been preferable from an environmental perspective. That is, replacing an organic solvent with a water-based solution is often desirable and can rightly be called “solvent-free.” However, under certain scenarios this substitution indeed could be environmentally unacceptable. Many toxic substances, such as certain heavy metal compounds, are highly soluble in water (i.e., hydrophilic). Is it possible that the water is a better transport medium for metal pigments in paint? Thus our “improved” process has actually made it easier for these metals contained in the solution to enter the ecosystem and to lead to human exposures. The lesson here is to be ever mindful of the *law of unintended consequences*.

Another consideration in the new paradigm is that waste reduction and elimination must not be justified solely using a cost-benefit economics, such as those based on the return on monetary investment that can be expected over the life of a product. Often, the waste manager is presented with a list of options, but they all begin with the waste arriving at the facility. Obviously, the manager’s span of control dictates the number and diversity of options.

However, even if limited in options, it is incumbent on the manager to suggest upstream improvements. Products that end up in the waste stream must also be evaluated using methods beyond a comparison of the initial investment as a fraction of the total cost of manufacture, use, and disposal. Product design decisions must also include less tangible impacts on the individual, society, and ecology that may not fit neatly on a data spreadsheet.

3.2 Traditional Facility Design

The critical path from product conception to completion has changed very little over thousands of years. The actual view of the process of design, however, varies substantially, even within the waste management community. The traditional design process from conception to completion has been sequential with distinct phases guiding the process from definition of need, drawings through technical development, fabrication, and final completion. The progression of the stepwise process from idea to realization is a sequence of events and involvement of specialized expertise. The process is direct, sequential, and linear, following a prescribed set of activities that will lead to a final solution [4].

This stepwise approach is often referred to as the “waterfall model,” drawing on the analogy of water flowing continuously through the phases of design. This approach is acceptable if the number of variables is manageable and a limited universe of possible solutions is predictable. An example of this approach would include a “prototype” design that is simply being adapted to a new condition. This process is often the most direct, conventional, and least costly when “first cost” is a primary consideration. For example, a reduction in the time required for design and delivery can mitigate the impact of price escalation due to inflation and other market variables. In practice, many designs are planned around schedules that appear to be linear, but the actual activity within

each phase tends to be somewhat nonlinear (e.g., feedback loops are needed when unexpected events occur) [4].

Linear progression of the process would logically begin with a clear definition of the intended use. This assumes that the product use scenarios have been clearly identified and that the variability of uses well understood. This would mean that the data about users and uses are ample, which is seldom the case. Once these data are collected and characterized, alternatives for meeting the use requirements are woven into a framework or *schematic* for the new product. The design process optimizes on the basis of predetermined design criteria.

3.3 Comprehensive Approach

Historically, products have been designed as an unqualified handoff, at least in terms of what to do with any waste products generated during and after the intended use. Such an approach considers only a type of contractual arrangement between the manufacturer and user that the product will perform according to specific criteria. Other stages in the product’s life (e.g., waste streams) are not part of this “contract.” This has been one of the failings of the traditional design process, that is, underweighting or completely ignoring the wastes that would be generated, not only in the fabrication step, but throughout the product life. Thus beginning in the late 20th century, designers began to embrace DfD, that is, identifying and managing the materials from the product that will be present after the useful life.

Designing without respect to disassembly was evident in a magazine advertisement in the 1970s, which showed a hand throwing away a disposable razor. The razor simply disappeared. Conversely, we can safely assume, given the biodegradation rates of the plastics used in the razor, that the handle is still intact in a landfill somewhere. Thus DfD goes beyond evaluating the disposition of materials, vacated

land, contamination of manufacturing facilities, and other remnants of the project. It is also a view of utility beyond the use phase, that is, “repurposing” the remaining materials. Certainly, this requires postuse planning, such as insisting on the use of reusable materials and considerations of obsolescence of parts and the entire system. It also addresses uses after the first stage of usage and the avoidance (“down cycling”). For example, if a neighborhood demographic were to change in the next century, is the design sufficiently adaptive to continue to be useful for this new set of users? This is not so unusual, as in the case of well-planned landfills, which may have a few decades of waste storage, followed by many decades of park facilities. How many strip malls or shopping centers were designed for but a few decades of use, followed by abandonment and desolation of neighboring communities in their wake? It is folly and professional hubris to assume that the user community will not change with respect to its social milieu. Product design must embrace the idea of “long-life/loose fit” and be sufficiently flexible to accommodate a variety of adaptive reuse scenarios.

4 LIFE CYCLE ASSESSMENT

The complexity of life cycle assessment ranges from scant attention to inputs and outputs of materials and energy (Fig. 2.1), to multifaceted decision fields extending deeply into time and space. The latter is preferable for decisions involving large scales, such as the cumulative buildup of greenhouse gases, or those with substantially long-term implications, such as the release of genetically altered microbes into the environment. Complex LCAs are also favored over cursory models when the effects are extensive, such as externalities and artifacts resulting in geopolitical impacts.

Selecting appropriate waste technologies, such as biotechnologies, will rely on complex

LCAs, but that does not mean every choice needs a unique LCA. For example, there may be similarities to an existent system that can be applied, with adjustments to account for the unique waste scenario at hand. Thus the data needed depend on goal and scope of the LCA, including:

- (a) time-related coverage: age of data and the minimum length of time over which data should be collected;
- (b) geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;
- (c) technology coverage: specific technology or technology mix;
- (d) precision: measure of the variability of the data values for each data expressed (e.g., variance);
- (e) completeness: percentage of flow that is measured or estimated;
- (f) representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e., geographical coverage, time period, and technology coverage);
- (g) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;
- (h) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;
- (i) sources of the data; and,
- (j) uncertainty of the information (e.g., data, models and assumptions).

A vital part of LCA is the determination of the environmental impact of a process, known as the life cycle impact assessment (LCIA). This is the “so what” analysis, which makes use of characterization factors (CFs), that is, weighting factors used in the LCIA. The impact score (S) is a function of the CF and the amount of matter or

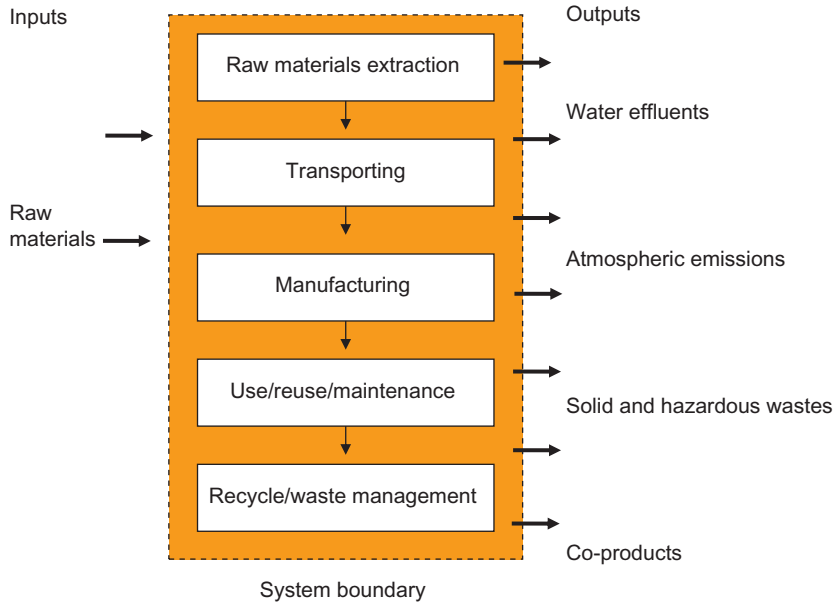


FIG. 2.1 Life cycle stages of a process must follow the conservation law, with material and energy balances.
Modified from US Environmental Protection Agency.

energy input. For example, the impact on human health from a waste process emission can be calculated as:

$$S = \sum_i \sum_x CF_{x,i} \times M_{x,i} \quad (2.1)$$

where S is the human health impact score, $CF_{x,i}$ is the characterization of substance x emitted from the process and released to compartment i , and $M_{x,i}$ is the mass of x emitted to compartment i .

An environmental LCIA converts emissions into impact scores for various impact categories. An impact score is a weighted sum of the damage due to all pollutant releases to one of these or other impact categories [5]. LCAs generally and LCIA specifically provide a systematic view of the costs and benefits of an entire process rather than a single stage of the life cycle. For pollution, LCAs allow the engineer or process designer to compare among various alternatives. For example, a chemical compound may appear to be the

best choice for manufacturing a product, but the LCIA may indicate that it will produce a toxic pollutant in later stages, which will have to be treated to a level of safety. The treatment will add costs and risks that can be prevented by changes in process design or selection of safer chemicals which, if substituted, may eliminate or greatly reduce the treatment costs. Similarly, the LCA may indicate that a choice of a substance may increase the generation and release of pollutants in earlier stages, such as the extraction of ores, which would not occur or would occur at a safer level if another substance with less extraction-related pollution is selected.

Because health risk is a function of and exposure, the human health CF, reliable risk predictions depend on a number of factors that differ among pollutants. Accounting for near-field scenarios and incorporating these into sustainability tools is becoming part of the LCA process.

An LCA can be conducted in numerous ways, including the application of spreadsheets to

TABLE 2.1 Example Summary Table From Single Indicator

Step 1				Step 2		Step 3	
				Factor		Score	
Materials	Steel	0.8	kg	0.49	€ kg ⁻¹	0.392	€
	Polypropylene	0.3	kg	1.02	€ kg ⁻¹	0.306	€
Production	Electroplating chromium	0.2	m ²	2.28	€ m ⁻²	0.456	€
Transport	Sea container	21	tonnes	0.0052	€ kg ⁻¹	0.109	€
Use	Electricity	3.6	kWh	0.109	€ kg ⁻¹	0.392	€
End of life	Landfill	1.1	kg	0.118	€ kg ⁻¹	0.130	€
	Total					1.785	€

This method assigns costs of the environmental burden of a product based on the costs to eliminate that burden. For example, for each kg of a substance that is produced that harms habitat, €2 might have to be invested in pollution control equipment and wetland construction.

From J. Vogtlander, *Eco-efficient Value Creation, Sustainable Strategies for the Circular Economy*, Delft Academic Press, 2014. Used with permission from Delft Academic Press/VSSD

build an inventory based on a list of life cycle elements, for example, energy, materials, transport, and pollutant treatment, and to add an indicator factor from a lookup table or open access software. The example of a spreadsheet LCA in Table 2.1 shows the eco-costs of a product as the sum of all eco-costs of emissions and use of resources during the entire life cycle. This can be used to compare alternative approaches and find substitute materials and processes to produce the same product with less environmental and human health insult, for example, among various waste management types.

The publicly available Open LCA is a more complicated system than the spreadsheet approach. For example, the Open LCA software was used to present the flowchart in Fig. 2.2. The calculated CFs are presented in Table 2.2. The LCA provides waste managers with alternatives, including product and chemical substitutions, end-of-life and recycling comparisons, and carbon and energy footprints among alternatives. The LCA is also very useful in visualizing possible social issues related to waste disposal, recycling, and environmental justice (See Fig. 2.3 and Table 2.2).

The life cycle inventory (LCI) and other components of an LCA draw data from varied sources, but the data themselves are stored in a computer-based information system (CBIS). A database system is a sharable CBIS that consists of an organized set of data that have been gathered for specific purposes, not necessarily intended for waste management. The database system is built from software that connects the user to the data. The data exist in spatial, tabular, spreadsheet, and other forms. For example, the United Kingdom's open or so-called big data web-based systems that are useful for waste managers include WasteData-Flow [6] for municipal waste data, National Packaging Waste Database [7] for packaging recycling and recovery data, and WasteConect [8] for recycling data. Big data sources that are not specifically built for wastes, but which contain useful information, include the National Climatic Data Center, which produces climate data for US hydrological regions; the US Department of Agriculture's National Statistical Service, which generates the Agricultural Resource Management Survey (crop and nutrient data); and the US Energy Information

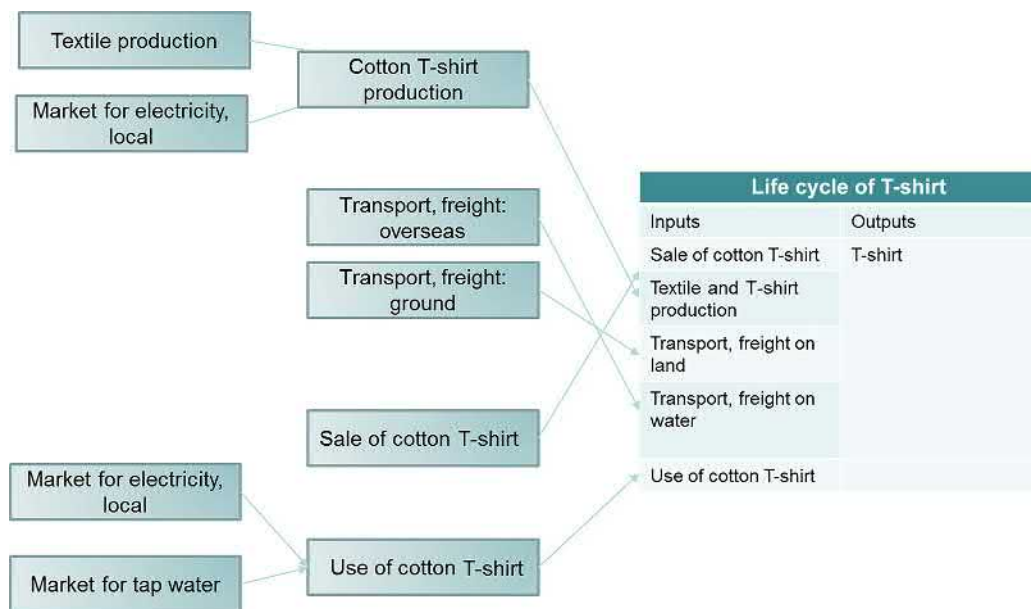


FIG. 2.2 Life cycle of a T-shirt. Modified from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017; Modified from F. Eisfeldt, F. Möller, *Social and Environmental Impacts of a T-Shirt: A Life Cycle Approach*, Presented at the Ethical Fashion Show Berlin, Berlin, Germany, January 19, 2017.

TABLE 2.2 Life Cycle Impact Values for Current Approach to Manufacturing a T-shirt

Impact Category	Result	Reference Unit
Agricultural land occupation	5.03	m ² times year (m ² a)
Climate change	22.5	kg carbon dioxide equivalent (eq)
Fossil fuel depletion	5.51	kg oil eq
Freshwater ecotoxicity	0.75	kg 1,4 dichlorobenzene eq (kg 1,4-dBeq)
Freshwater eutrophication	0.02	Kg phosphorus eq
Human toxicity	17.44	kg 1,4-dBeq
Ionizing radiation	5.64	kg U-235eq
Marine ecotoxicity	0.01	kg 1,4-dBeq
Marine eutrophication	0.01	Kg nitrogen eq
Metal depletion	1.49	kg iron eq
Natural land transformation	2.3×10^{-3}	m ²
Ozone layer depletion	3.6×10^{-5}	kg chlorofluorocarbon eq
Particulate matter formation	0.04	kg PM-10eq

TABLE 2.2 Life Cycle Impact Values for Current Approach to Manufacturing a T-shirt—Cont'd

Impact Category	Result	Reference Unit
Photochemical oxidant formation	0.05	kg nonmethane VOC eq
Terrestrial acidification	0.09	kg sulfur dioxide eq
Terrestrial ecotoxicity	0.11	kg 1,4-dBeq
Urban land occupation	0.16	m ² a
Water depletion	124.75	m ³

Data from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Data from F. Eisfeldt, F. Möller, *Social and Environmental Impacts of a T-Shirt: A Life Cycle Approach*, Presented at the Ethical Fashion Show Berlin, Berlin, Germany, January 19, 2017.

Administration and EPA, which produce the Emissions and Generation Resource Integrated Database (resource mix, heat, air pollutant emissions from electricity generation).

The decision to increase the use of ethanol as a fuel additive and a reformulated fuel provides an example in which science and policy considerations were conjoined. Alternative fuel standards have met with skepticism and even descent. In particular, the viability of ethanol is being challenged from scientific and policy standpoints. Corn-based ethanol is indeed a biotechnology. In fact, since the presidential proclamation, dedicated corn crops and bioreactors in these states have emerged. On the other hand, geopolitical impacts, such as food versus fuel dilemmas are being raised. Scientific challenges to any improved efficiencies and actual decreases in the demand for fossil fuels have also been voiced. Some have accused advocates of ethanol fuels of using “junk science” to support the “sustainability” of an ethanol fuel system. Notably, some critics contend that ethanol is not even renewable, since its product life cycle includes a large number of steps that depend on fossil fuels. The metrics of success are often deceptively quantitative. For example, the two goals for increasing ethanol use include firm dates and percentages. However, the means of accountability can be quite subjective.

For example, in his 2007 State of the Union Address, US President George W. Bush set a goal to reduce gasoline consumption by 20% over the next 10 years. This 2017 goal *could have been* met, but would have required overall fossil fuel use would have to had declined dramatically. Indeed, the gasoline consumption has remained fairly constant (See Fig. 2.4) [9]. Thus *both* absolute and fractional metrics were needed.

Another accountability challenge is how accurately energy and matter losses are included in calculations. From a thermodynamics standpoint, the nation's increased ethanol use could actually increase demands for fossil fuels, such as the need for crude oil-based infrastructures, including farm chemicals derived from oil, farm vehicle and equipment energy use (planting, cultivation, harvesting, and transport to markets) dependent on gasoline and diesel fuels, and even embedded energy needs in the ethanol processing facility (crude oil-derived chemicals needed for catalysis, purification, fuel mixing, and refining). A comprehensive LCA is a vital tool for ascertaining the actual efficiencies.

The questions surrounding life cycles of products like ethanol can be addressed using a three-step methodology. First, the efficiency calculations must conform to the physical laws, especially those of thermodynamics and motion. Second, the “greenness,” as a metric of sustainability and effectiveness can be characterized by

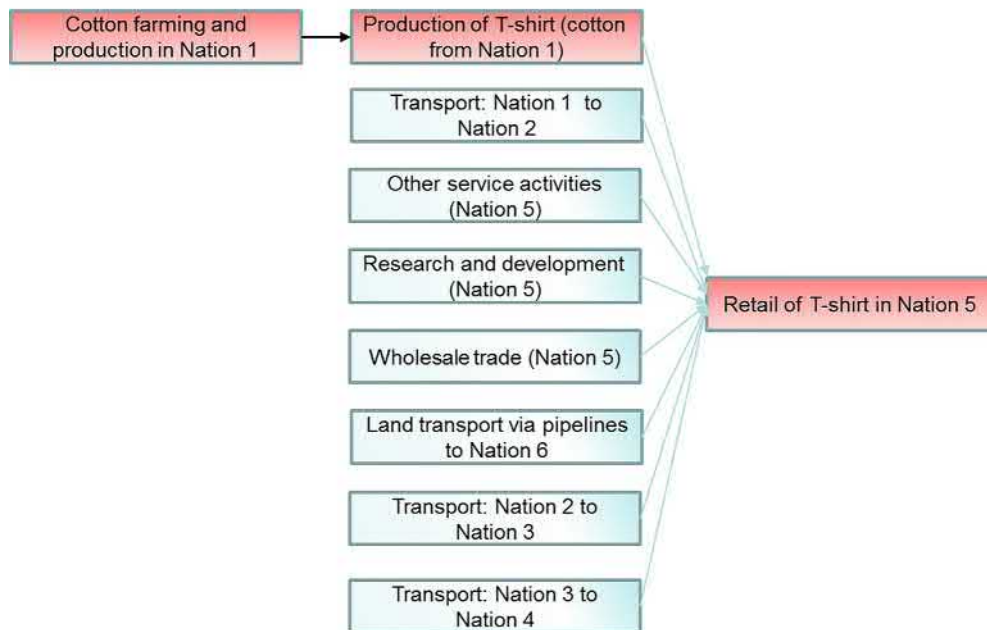
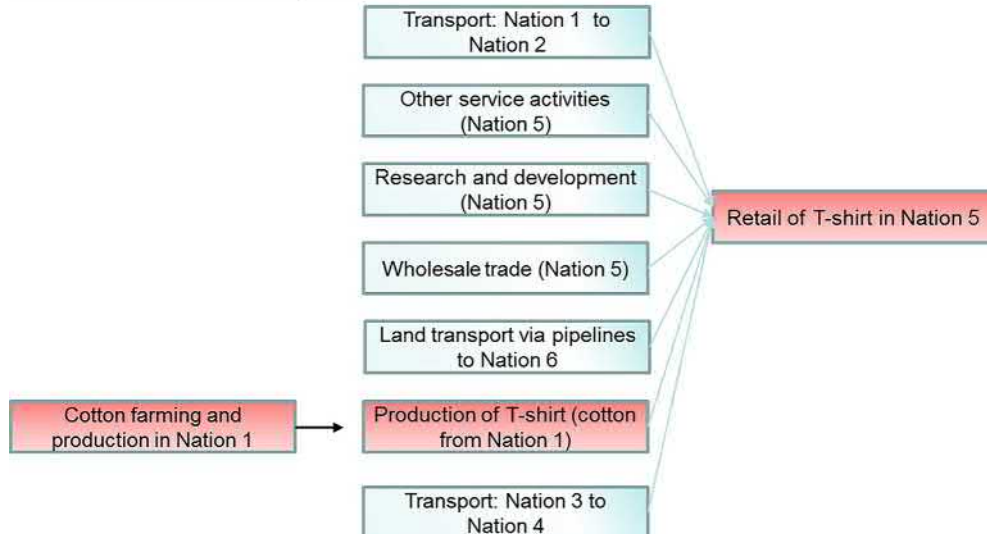
Scenario: Cotton from developing nation**Scenario: Fair trade life cycle assessment**

FIG. 2.3 Comparisons of three alternative scenarios for making and transporting a T-shirt. Modified from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017; Data from F. Eisfeldt, F. Möller, *Social and Environmental Impacts of a T-Shirt: A Life Cycle Approach*, Presented at the Ethical Fashion Show Berlin, Berlin, Germany, January 19, 2017.

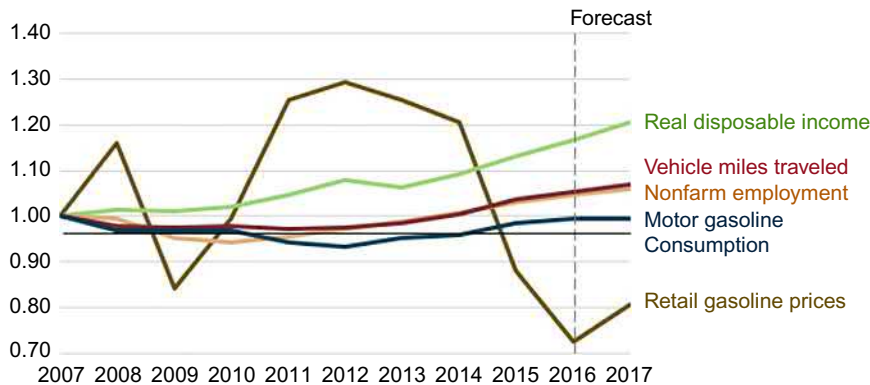


FIG. 2.4 Motor gasoline consumption and prices, compared to other macroeconomic indicators. Modified from U.S. Energy Information Administration. Motor Gasoline Consumption Expected to Remain below 2007 Peak despite Increase in Travel, 2016. Available from: <https://www.eia.gov/todayinenergy/detail.php?id=25072> (Accessed 5 March 2018).

life cycle analyses. Third, the policy and geopolitical options and outcomes can be evaluated by decision force field analyses. In fact, these three approaches are sequential. The first must be satisfied before moving to the second. Likewise, the third depends on the first two methods. No matter how political attractive or favorable by society, an alternative fuel must comport with the conservation of mass and energy. Further, each step in the life cycle (e.g., extraction of raw materials, value-added manufacturing, use, and disposal) must be considered in any benefit-cost or risk-benefit analysis. Finally, the societal benefits and risks must be viable for an alternative fuel to be accepted. Thus even a very efficient and effective fuel may be rejected for societal reasons (e.g., religious, cultural, historical, or ethical).

The challenge is to sift through the large and diverse data sets to ascertain whether ethanol truly presents a viable alternative fuel. Of the misrepresentations being made, some clearly violate the physical laws. Many ignore or do not provide correct weights to certain factors in the life cycle. There is always the risk of mischaracterizing the social good or costs, a common problem with the use of benefit-cost relationships.

4.1 Efficiency

Fuel efficiencies are evaluated in terms of net energy production that is based on thermodynamics (first and second laws). Energy balances can be calculated from the first law of thermodynamics:

$$\begin{aligned} \text{Accumulation} &= \text{creation rate} \\ &\quad - \text{destruction rate} + \text{flow in} \\ &\quad - \text{flow out} \end{aligned} \quad (2.2)$$

Stated quantitatively as efficiency:

$$\text{Efficiency} = \frac{E_{\text{in}} - E_{\text{out}}}{E_{\text{in}}} \times 100 \quad (2.3)$$

where,

E_{in} = Energy entering a control volume, and
 E_{out} = Energy exiting a control volume

The numerator includes all energy losses. However, these are dictated by the specific control volume. This volume can be of any size from molecular to planetary. To analyze energy losses related to alternative fuels, every control volume of each step of the life cycle must be quantified.

The first two laws of thermodynamics drive this step. First, the conservation of mass and

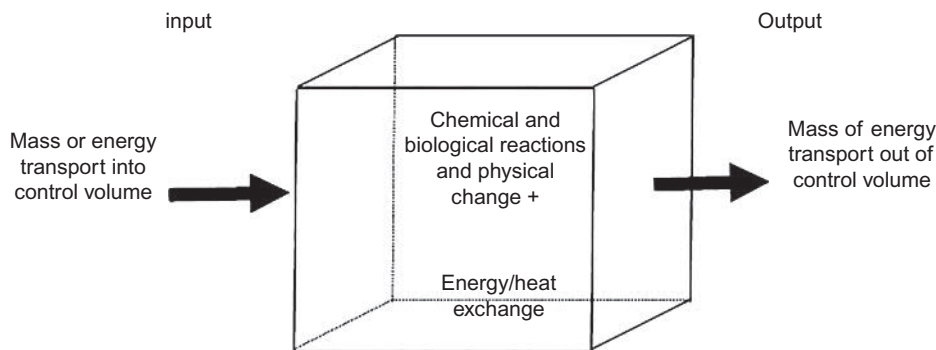


FIG. 2.5 Control volume showing input, change, and output. The process applies to both mass and energy balances. Modified from L. Sommer, *Design for the environment program*, in: *Exposure-Based Chemical Prioritization Workshop*, Research Triangle Park, North Carolina, 2010 (EPA).

energy requires that every input and output be included. Energy or mass can neither be created nor destroyed, only altered in form. For any system, energy or mass transfer is associated with mass and energy crossing the control boundary within the control volume (Fig. 2.5). If mass does not cross the boundary, but work and/or heat do, the system is a “closed” system. If mass, work, and heat do not cross the boundary, the system is an isolated system. Too often, open systems are treated as closed, or closed systems include too small of a control volume. A common error is to assume that the life cycle begins at an arbitrary point conveniently selected to support a benefit-cost ratio. For example, if a life cycle for ethanol fuels begins with the corn arriving at the ethanol processing facility, none of the fossil fuel needs on the farm or in transportation will appear.

The second law is less direct and obvious than the first. In all energy exchanges, if no energy enters or leaves the system, the potential energy of the state will always be less than that of the initial state. The tendency toward disorder, that is, entropy, requires that external energy is needed to maintain any energy balance in a control volume, such as a heat engine, waterfall, or an ethanol processing facility. Entropy is ever present. Losses must always occur in conversions from

one type of energy (e.g., mechanical energy of farm equipment ultimately to chemical energy of the fuel). Thus Eq. (2.3) is merely an expression of net inputs, net outputs, and net system losses. The efficiency is actually a series of energy balances equations for the entire process, with losses at every step.

These equations illustrate the importance of reliable information in the LCI. Any LCA relies on the LCI data to assess the environmental implications associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases. From this LCI, the potential environmental impacts are evaluated. The results aid in decision making. Thus the LCA process is a systematic, four-component process:

1. *Goal Definition and Scoping*: Define and describe the product, process, or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.
2. *Inventory Analysis*: Identify and quantify energy, water, and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).

3. *Impact Assessment*: Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
4. *Interpretation*: Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process, or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

Note that these steps, as illustrated in Fig. 2.6, track closely with the life cycle stages dictated by the laws of physics. Also, the life cycle can help to highlight possible routes and pathways of exposure to constituents during extraction, manufacture, use, and disposal (See Fig. 2.7). This can drive the availability of safer products, that is, design for the environment (DfE). The

DfE process shown in Fig. 2.8 indicates that the life cycle can have a number of stages where a product can be made safer, resulting in a product that is less toxic and/or where the user is less exposed to the product's toxic constituents. Either of these would reduce the product's risk. From a waste management perspective, DfE the collective effect of these safer products can translate into less toxic loading to the waste stream at the end-of-product life stage.

This stepwise process can be used to evaluate products long before a waste is generated. First, a LCI is constructed to define the boundaries of the possible effects of a technology (e.g., microbial populations, genetically modified organisms, and toxic chemical releases). If the technology is hypothetical, this can be done by analogy with a similar conventional process. Next, experts can participate in an expert panel to find the driving forces involved (this is known

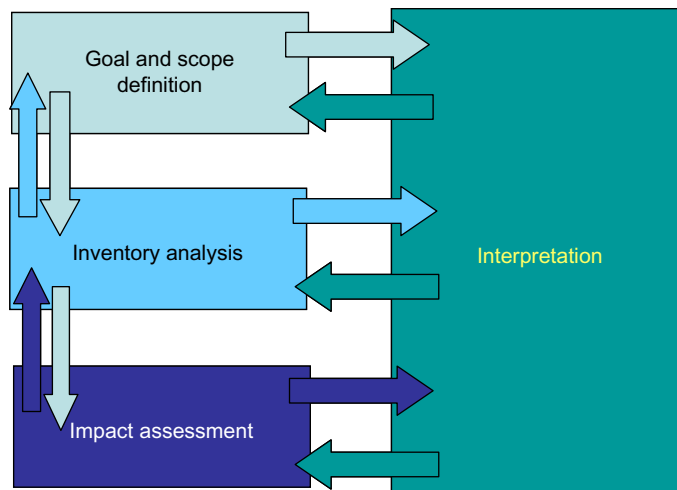


FIG. 2.6 Life cycle assessment framework consists of: (1) a specifically stated purpose of boundaries of the study (Goal and Scope Definition); (2) an estimate of the energy use and raw material inputs and environmental releases associated with each stage of the life cycle (Life Cycle Inventory); (3) an interpretation of the results of the inventory to assess the impacts on human health and the environment (Impact Assessment); and (4) an evaluation of ways to reduce energy, material inputs, or environmental impacts along the life cycle (Interpretation). *Courtesy: D. Vallero, Environmental Biotechnology: A Biosystems Approach. Elsevier Science, 2015.*

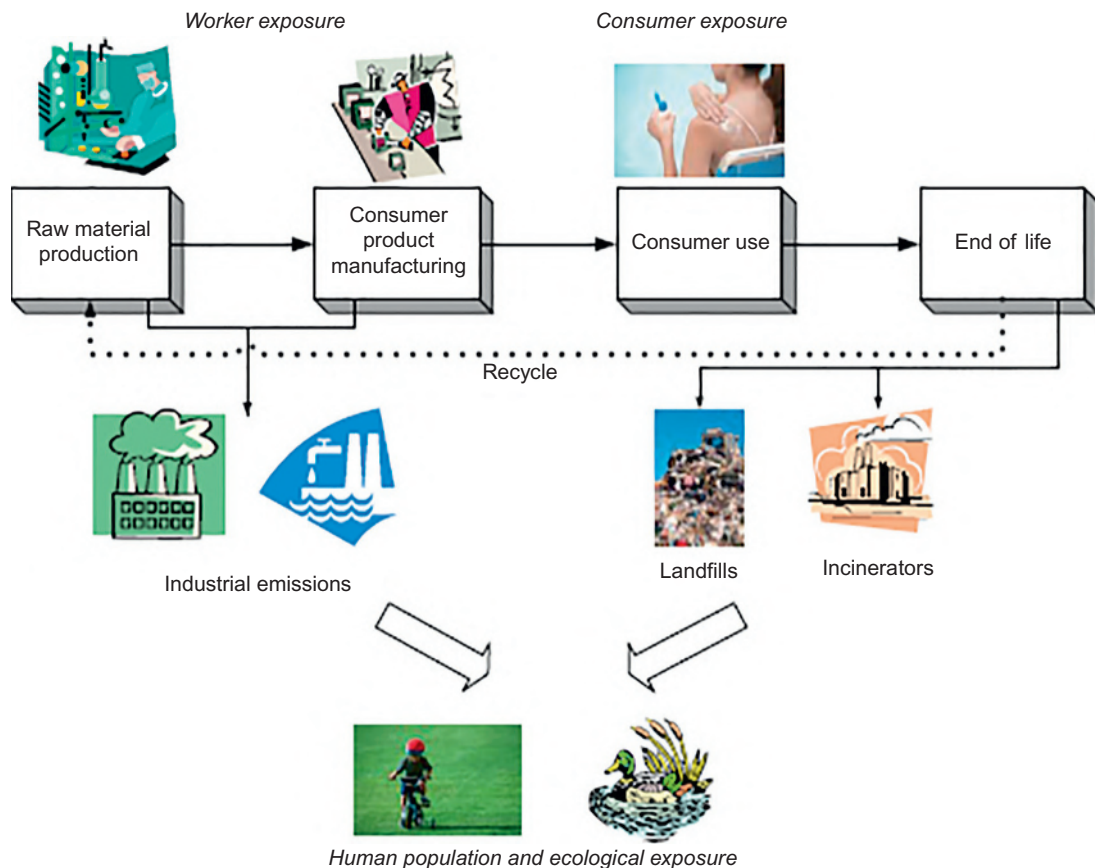


FIG. 2.7 Life cycle of product, showing points of exposure and potential risk, including after the useful life of the product. Modified from U.S. Environmental Protection Agency, *Systems Analysis Research: Program Brief-Life Cycle Analysis*, 2009.

as “expert elicitation”). Then, scenarios can be constructed from these driving forces to identify which factors are most important in leading to various outcomes. This last step is known as a sensitivity analysis. The greater the weight of the factor the greater will be the change in the outcome. For example, if a product has a very small waste stream of a product that damages an ecosystem, but another product has 100 times the waste stream of the same chemical constituents, then the ecosystem is 100 times more sensitive to the latter product than the former in the prescribed ecosystem.

4.2 Utility and the Benefit-Cost Analysis

On the surface, the choice of whether to pursue a waste disposal option is a simple matter of benefits versus costs. Is it more or less costly to dispose of substance A using approach 1, 2, or n ? Engineers make much use of the benefit-cost ratio (BCR), owing to a strong affinity for objective measures of successes. Thus *usefulness* is an engineering measure of success. Such utility is indeed part of any successful engineering enterprise. After all, engineers are expected to

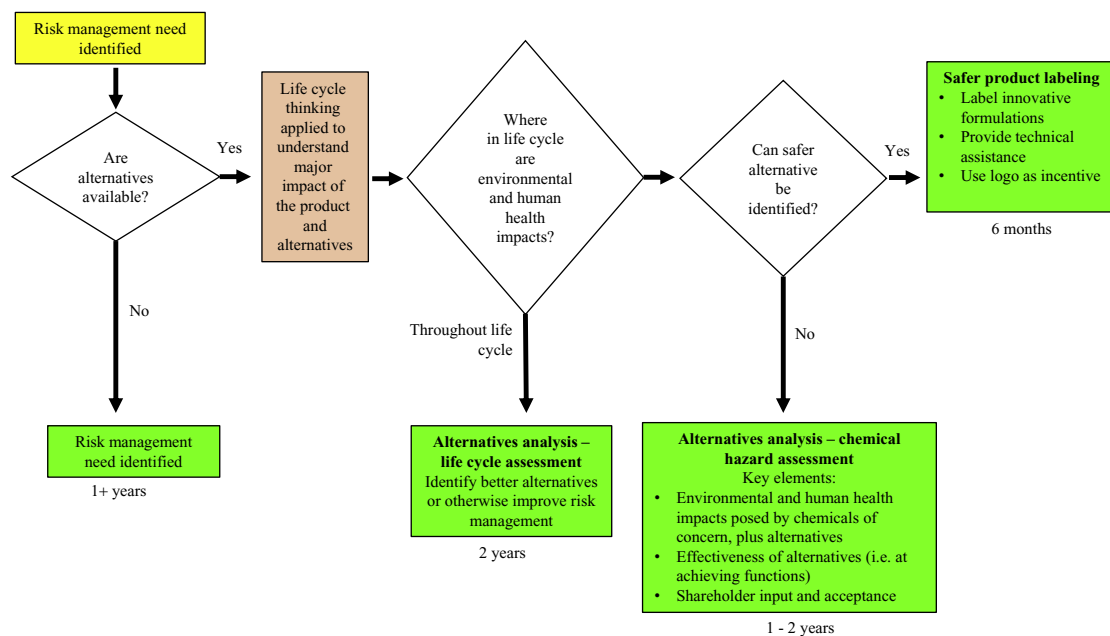


FIG. 2.8 Decision logic for design for environment (DfE) approaches. Modified from L. Sommer, *Design for the environment program*, in: *Exposure-Based Chemical Prioritization Workshop*, Research Triangle Park, North Carolina, 2010. (EPA).

provide reasonable and useful products. Two useful engineering definitions of utilitarianism (Latin *utilis*, useful) are imbedded in BCR and LCA:

1. The belief that the value of a thing or an action is determined by its utility.
2. The concept that effort should be directed toward achieving the most benefit for the greatest number.

The BCR is an attractive metric due to its simplicity and seeming transparency. To determine whether a project is worthwhile, one need only add up all of the benefits and put them in the numerator and all of the costs (or risks) and put them in the denominator. If the ratio is >1 , its benefits exceed its costs.

One obvious problem is that some costs and benefits are much easier to quantify than others. Some, like those associated with quality of life,

are nearly impossible to quantify and monetize accurately. Further, the comparison of action versus no-action alternatives cannot always be captured within a BCR. Opportunity costs and risks are associated with taking no action (e.g., loss of an opportunity to apply an emerging technology may mean delay or nonexistent treatment of diseases).

Simply comparing the *status quo* to costs and risks associated with a new product may be biased toward no action or proven technologies. Costs in time and money are not the only reasons for avoiding action. The greater availability of a product may introduce unforeseen risks that, if not managed properly, could lead to waste products that could add costs to the public (e.g., pollution or loss of ecosystem diversity) with only short-term value and little net benefit. So, it is not simply a matter of benefits versus cost, it is often one risk being traded for another.

Often, selecting a critical path, including various waste streams, is a matter of optimization, which is a proven analytical tool in engineering. However, the greater the number of contravening risks that are possible, the more complicated that such optimization routines become. The product flows, critical paths, and life cycle inventories can become quite complicated for complex issues.

5 SUSTAINABILITY

The World Commission on Environment and Development, known as the Brundtland Commission and sponsored by the United Nations, recognized an impending global threat of environmental degradation. As such, the Commission conducted a study of the threats to the planet and issued the 1987 report, *Our Common Future*, which introduced the term *sustainable development*, defined as:

... development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The United Nations Conference on Environment and Development, that is, the Earth Summit held in Rio de Janeiro in 1992 communicated the idea that sustainable development is both a scientific concept and a philosophical ideal. The document, *Agenda 21*, was endorsed by 178 governments (not including the United States) and hailed as a blueprint for sustainable development.

In 2002 the World Summit on Sustainable Development identified five major areas that are considered key for moving sustainable development plans forward. Sustainable development particularly targets support to developing nations in managing their resources, such as rain forests, without depleting these resources and making them unusable for future generations. The principal objective is to prevent the collapse of the global ecosystems, tying directly with finding ways to eliminate and to reduce the

generation of wastes, which stress these ecosystems. The Brundtland report does not provide specific details on just how to achieve a sustainable global ecologic and economic system, meaning that green and sustainable actions are increasingly dependent on the advice from experts like the authors of the chapters in this book.

A sustainable system is at thermodynamic equilibrium or only slightly changing. The difference between a sustainable and unsustainable system is subjective, since so many variables exist in complex systems. In fact, a system can become unsustainable over time, such as when a landfill nears capacity. Under some conditions, however, even a very sustainable system will fail if disrupted severely by an event like a spill or other major disruption.

A food chain provides an example of an environmental system that is affected potentially by waste management decisions. Microbial and plant growth and productivity depend on sunlight, moisture, and nutrients. This cell growth, for example, catabolism, makes food for high order organisms, that is, herbivores, whose cells become food for larger animals. The waste from these animals replenishes the soil, which nourishes plants, and the cycle begins anew. Such distributions of mass and energy occur continuously among and within the compartments of the food chains, with humans among the consumers. Food chains illustrate the complexity and vulnerability of environmental systems (see Fig. 2.9). The species at a higher tropic level are predators of lower level species, so that matter and energy flow downward. The transfer of mass and energy upwardly and downwardly between levels of biological organization is measurable and predictable, given certain initial and boundary conditions. The types and abundance of species and interaction rates vary temporally and spatially. From a waste management standpoint, the introduction of chemical toxins or changes in environmental conditions (e.g., introduction of nutrients and toxic by-products) can change these trophic interrelationships.

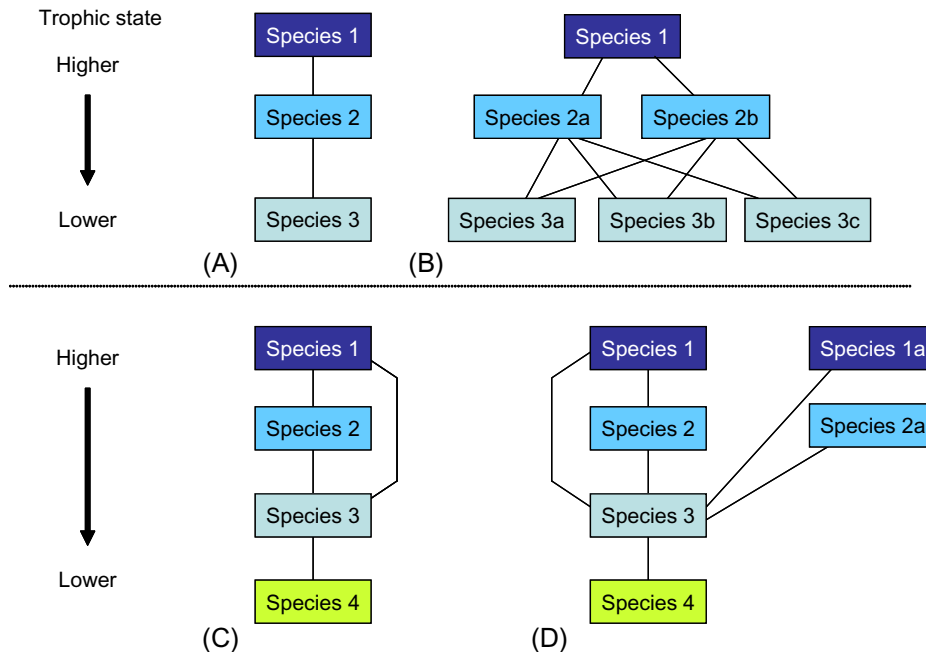


FIG. 2.9 Energy and matter flow in environmental systems from higher trophic levels to lower trophic levels. Lines represent interrelationships among species. (A) Linear biosystem, (B) Multilevel trophic biosystem, (C) Omnivorous biosystem, and (D) Multilevel biosystem with predation and omnivorous behaviors. An interference at any of these levels or changes in mass and energy flow can lead to disasters. Courtesy: D. Vallero, Excerpt: *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015; based on information from: T.E. Graedel, On the concept of industrial ecology, *Annu. Rev. Energy Environ.* 21 (1) (1996) 69–98.

All systems have thermodynamic inefficiencies, as articulated in the second law of thermodynamics. Arguably, the largest disruptions are the result of human activities, manufacturing, transportation, commerce, and other human activities that promote high consumption and wastefulness of finite resources cannot be sustained indefinitely. As such, matter and energy balances and losses from processes long before the end of a product's useful life. Thus sound waste management both depends upon and influences sustainable practices.

5.1 The Tragedy of the Commons

The interconnectedness and need for sustainable means of reducing wastes may be illustrated by a parable presented by biologist, Garrett Hardin, who imagines an English village

with a common area where everyone's livestock may graze. The common is able to sustain the animals, making for stable village life, until one of the villagers figures out that if he raises two animals instead of one, the cost of the extra animal will be shared by everyone, while the profit will be his alone. So he gets two animals and prospers, but others see this and similarly want their own two animals. If two, why not three—and so on—until the village common is no longer able to support the large number of animals, and everyone suffers when the system surpasses carrying capacity and crashes.

Ignorance is not bliss when we reach the threshold between capacity and failure. The good news is that we have sounded the alarm for the waste capacity. However, we must continue to take great care in preventing the problems before they arise. It is also a call to be

better stewards of our diminishing resources. In addition to reducing wastes, we must be mindful that fossil fuels, minerals, and other natural resources are finite. Treating them as capital gains may lead to tragedies of our “commons,” be they local or global.

6 CONCLUSIONS

The large volumes of waste generated daily throughout the world, but especially in developed regions, indicate a lack of a systems view and sustainable approaches. Although the chapters that follow devote considerable attention to these wastes and how they can be best managed, preventing the generation of wastes is preferable to handling and treating them. Wastes can be minimized or even eliminated by using greener approaches, which go beyond recycling, and call for systematic and comprehensive choices in the products demanded by society. Part of the solution is in the design of these products, as well as in making users aware of the life cycle of these products and the damage that can be avoided by innovative engineering and wise decision making. All such approaches and decisions must always be rooted in sound science.

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Further Reading

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Regulation of Wastes

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1 INTRODUCTION

Wastes are handled at every scale in widely varied ways. However, since waste is a societal problem, governments play key roles in their prevention and management. The roles can range from direct responsibility for the collection and treatment of wastes by municipalities to indirect controls, such as the enforcement of waste laws and ordinances by local and national agencies.

Environmental problems faced today differ from those of most of the earth’s history. The difference is in both kind and extent. The wastes themselves have changed, notably by the synthesis of chemicals, especially organic compounds, which have grown exponentially since the mid-1900s. Most organisms lack mechanisms to metabolize and eliminate these new compounds. The extent of environmental insults from human activities usually reached

only portions of ecosystems prior to the Industrial Revolution were small in extent of damage. For example, pollutants were discharged into creeks and rivers throughout human history, and these systems were often able to withstand the pollution given resilient biology, for example, microbial populations to metabolize the wastes. Only in the past two centuries did the wastes become so large and persistent that they have diminished the quality of entire ecosystems and threatened the health of large populated areas. Emerging technologies, such as genetic engineering and synthetic biology, could be introducing biological wastes that would require special handling and treatment.

In addition, world is becoming more urbanized, so that the pace of waste generation has increased in recent years. Municipal solid waste, worldwide, today is about 1.3×10^9 t (1.3 billion metric tonnes), which is expected to double by 2025 [1]. Waste has always been approached as a balance. Populations accept some waste to be generated as a by-product of something they value, for example, products and jobs. At some threshold, however, populations will demand actions be taken to reduce the waste, or at least the problems the waste is causing. This often translates into governance, with public expecting its elected and appointed delegates to enact laws, write rules and regulations, and ensure that waste generators comply [2].

From both a thermodynamic and economic perspective, the generation of wastes is indirectly proportional to efficiency. Waste is simply a resource that is out of place. Thermodynamically, the amount of energy that does not result in intended output, for example, work, is lost as waste (see Fig. 2.3 and Eq. 2.3 in Chapter 2). Economically, the inefficient use of resources causes scarce commodities to become less valuable or less fit to perform their useful purposes. For example, water pollution experts talk about a stream not meeting its “designated use,” such as recreation or public water supply. Thus if a landfill or other waste management facility releases contaminants, these can diminish the

quality of the receiving water to the point that its designated use would change. More importantly it threatens human health and the environment. Public health is usually held paramount in waste management decisions, but ecosystems are also important considerations. Other public values also come into play, such as esthetics. Even a well-managed waste site that is visually unsightly or which releases gases that result in nuisance odors would be considered to be economically inefficient [3, 4].

The number of laws enacted to address various aspects of wastes has grown substantially in recent decades [5]. The number and complexity of regulations have broadened commensurately (see Fig. 3.1). Like other environmental statutes and regulations, waste management throughout the world is underpinned by governance. For example, Europe has added numerous waste directives since the 1970s for both solid and hazardous wastes (see Fig. 3.2).

To assess and to address waste management appropriately and to make sound environmental decisions require at least a basic understanding of the underlying sciences affecting those issues, problems, and decisions. From a scientific perspective, waste management requires attention to the waste *and* the characteristics of the place where the waste is found. This place is known as the “environmental medium.” The major environmental media are air, water, soil, sediment, and even biota. In fact, the regulation of wastes is even more refined. Water, for example, is commonly categorized into “surface water” and “groundwater.” The former includes everything from puddles and rivulets, to large rivers and lakes, to the oceans. Although the various environmental disciplines apply some common language, they each have their own lexicons and systems of taxonomy. Sometimes the difference is subtle, such as different conventions in nomenclature and symbols. This is more akin to different slang in the same language. Environmental handbooks and texts use different conventions in explaining concepts and providing examples. Environmental information comes in many

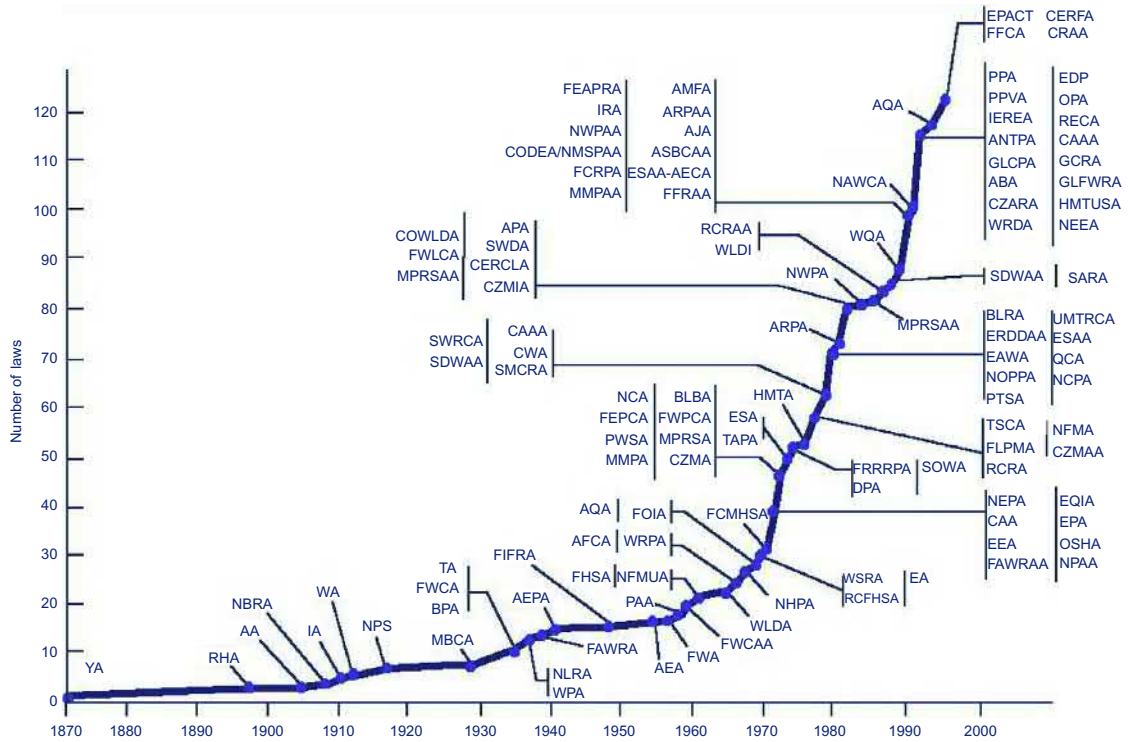
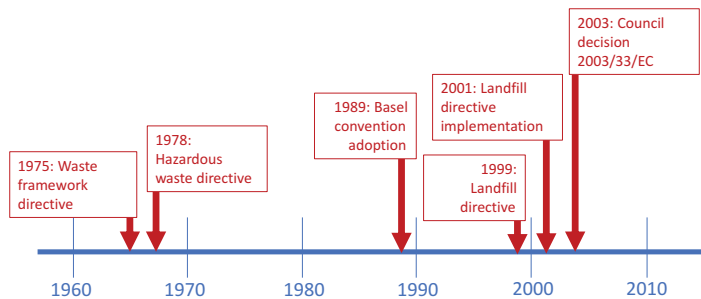


FIG. 3.1 Growth of environmental legislation in the United States during the 20th century. From D.R. Shonnard, *Environmental law and regulations: from end-of-pipe to pollution prevention*, in: D.T. Allen, D.R. Shonnard (Eds.), *Green Engineering: Environmentally Conscious Design of Chemical Processes*, Prentice Hall, Upper Saddle River, NJ, 2004, https://www.epa.gov/sites/production/files/2015-08/documents/green-engineering-textbook_508_0.pdf.

FIG. 3.2 Timeline of the European Union's waste directives. *Source:* A. Liu, F. Ren, W.Y. Lin, J.-Y. Wang, *A review of municipal solid waste environmental standards with a focus on incinerator residues*, *Int. J. Sustain. Built Environ.* 4(2) (2015) 165–188.



forms. A telling example is the convention the use of the letter "K." In hydrogeology, this means hydraulic conductivity, in chemistry it is an equilibrium constant, and in engineering it can be a number of coefficients. Likewise, units other than metric will be used on occasion, because that is

the convention in some areas, and because it demonstrates the need to apply proper dimensional analysis and conversions. Many mistakes have been made in these two areas.

Arguably, the two media that are most important to waste management are groundwater and

soil. Groundwater includes all water below the surface, but depending upon the discipline, is further differentiated from soil-bound water. Engineers commonly differentiate water in soil from groundwater because the soil water greatly affects the physical and mechanical properties of the soil horizons most commonly manipulated by human activities, especially agriculture and construction. Soil moisture, for example, affects the farmer's ability to till the soil and the road engineer's ability to calculate gel strength. By contrast, environmental engineering is principally concerned with the soil's ability to transport pollutants and to support microbial populations. Thus environmental publications frequently describe soil water according to the amount of void space filled, or the water filled pore space (WFPS), which is the percentage of

void space containing water. The WFPS is another way to express saturation.

Almost all environmental science professions classify the water below the soil layer based upon whether the unconsolidated material (e.g., gravel and sand) is completely saturated or unsaturated. The saturated zone lies under the unsaturated zone. Depending on the jurisdiction, the movement of contaminants in each section of Fig. 3.3 is regulated. For example, a landfill's leachate collection system may have to meet local, state, provincial, or national standards to limit the amount of contaminants that reach the groundwater. The landfill may also have to meet air quality standards for volatile organic compounds (VOCs) by the installation and operation of a landfill gas management system [6]. There are often numerous specifications

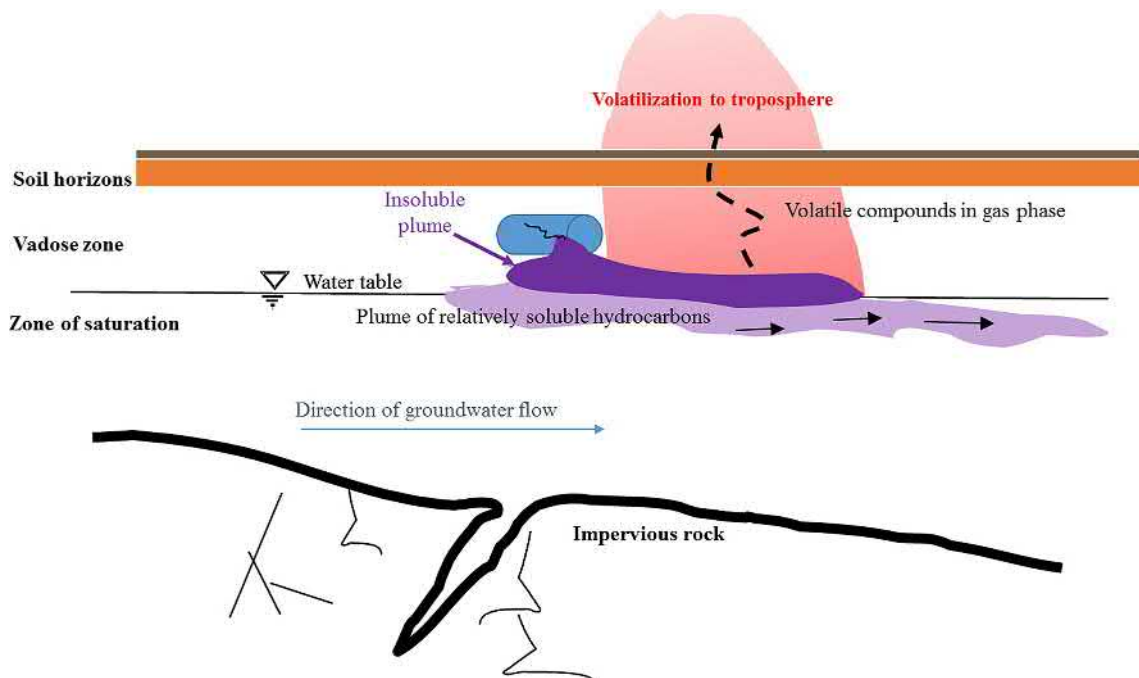


FIG. 3.3 A contaminant stored in underground unconsolidated material, for example, sand, may remain in the material for years, but with changes in meteorological conditions, soil disturbance, or continued leakage from a source, the material may move via the ground water flow, evade to the atmosphere (especially volatile compounds, i.e., those with higher vapor pressures), and/or sorb to the underground material in the vadose zone.

required by governments, including restrictions to protect surface waters, biota in ecosystems, and soils after the landfill closure.

Hydrogeologists refer to the unsaturated zone as the “vadose zone.” It is also referred to as the zone of aeration. Another type of groundwater, albeit rare, is the Karst groundwater system, which is actually made up of underground lakes and streams that flow through fractured limestone and dolomite rock strata. Small cracks in the rock erode over time to allow rapidly flowing water to move at rates usually seen only on the earth’s surface. Usually, groundwater flows quite slowly, but in these caves and caverns, water moves rapidly enough for its flow to be turbulent. We will cover all of these topics in detail when we discuss pollutant transport, drawing from several different scientific disciplines.

Soil scientists have struggled with uniformity in the classification and taxonomy of soil. Much of the rich history and foundation of soil science has been associated with agricultural productivity. The very essence of a soil’s “value” has been its capacity to support plant life, especially crops. Even forest soil knowledge owes much to the agricultural perspective, since much of the reason for investing in forests has been monetary. A stand of trees is seen by many to be a “standing crop.” In the United States, for example, the National Forest Service is an agency of the U.S. Department of Agriculture, not the Department of Interior. The agricultural and engineering perspectives have provided valuable information about soil that environmental professionals can put to use. The information is certainly necessary, but not completely sufficient, to understand how pollutants move through soils, how the soils themselves are affected by the pollutants (e.g., loss of productivity and diversity of soil microbes), and the soils and contaminants interact chemically (e.g., changes in soil pH will change the chemical and biochemical transformation of organic compounds). Waste managers require at least a

TABLE 3.1 Commonly Used Soil Texture Classifications

Name	Size Range (mm)
Gravel	>2.0
Very coarse sand	1.0–1.999
Coarse sand	0.500–0.999
Medium sand	0.250–0.499
Fine sand	0.100–0.249
Very fine sand	0.050–0.099
Silt	0.002–0.049
Clay	< 0.002

Source: T.E. Loynachan, K.W. Brown, T.H. Cooper, M.H. Milford, *Sustaining Our Soils and Society*, American Geological Institute, 1999.

modicum of understanding of how soils are classified according to their texture or grain size (see [Table 3.1](#)), ion exchange capacities, ionic strength, pH, microbial populations, and soil organic matter content.

Waste management facilities are comprised of matrices and fluids. Air and water are fluids that reside and move through the interstices of matrices within the facility. Sometimes it is difficult to separate the fluid from the matrix. For example, sediment resembles soil in that it is a matrix made up of various components, including organic matter and unconsolidated material, but some of these matrix substances also move as fluids, such as fulvic and humic acids. The liquids in the interstices are chemically known as “substrates,” which hold solutes (e.g., contaminants and nutrients).

The predominant volume of substrate in this matrix is usually water that contains varying amounts of solutes. At least for most environmental conditions, air and water are solutions of very dilute amounts of compounds. For example, air’s solutes represent small percentages of the solution at the highest (e.g., water vapor) and most other solutes represent parts per million (CO₂ is about 400 ppm). Most “contaminants” in air and water, thankfully,

are found in the parts per billion range, if found at all. On the other hand, soil and sediment themselves are conglomerations of all states of matter. Soil is predominantly solid, but frequently has large fractions of liquid (soil water) and gas (soil air, methane, carbon dioxide) that make up the matrix. The composition of each fraction is highly variable. For example, soil gas concentrations are different from those in the atmosphere and change profoundly with depth from the surface. For example, Table 3.2 presents the inverse relationship between carbon dioxide and oxygen.

Ecosystems are amalgamations of all of the previously mentioned media. For example, a wetland system consists of plants that grow in soil, sediment, and water. The water flows through living and nonliving materials. Microbial populations live in the surface water, with aerobic species congregating near the water surface and anaerobic microbes increasing with depth due to the decrease in oxygen levels, due to the reduced conditions. Air is not only important at the water and soil interfaces, but it is a vehicle for nutrients and contaminants delivered to the wetland. The groundwater is fed by the surface water during high water conditions and feeds the wetland during low water.

Thus one of the profound challenges in regulating wastes is that the problems they introduce are complicated and involve many aspects of the environment. A glance at Fig. 3.1 indicates that environmental laws most often address a single environmental medium, for example, the Clean Air Act, the Clean Water Act, or Safe Drinking Water Act. Waste originates and some of its constituents and degradation products move through all the media, which may be envisioned as thermodynamic compartments, each with its own boundary conditions, kinetics, and partitioning relationships and which interacts and shares energy and matter with other compartments. Chemicals, whether nutrients or contaminants, change as a result of the time spent in each compartment. The waste manager's challenge is to describe, characterize, and predict the behaviors of waste constituents as they move through the media. When something is amiss, the cause and cure lie within the physics, chemistry, and biology of the system. Thus waste regulations must be underpinned by sound science.

Love Canal in New York, for example, became the waste case that catalyzed concern and led to the passage of hazardous waste laws. Though the problem gained notoriety over four decades ago, it remains one of the most complex

TABLE 3.2 Composition of Two Important Gases in Soil Air

Depth From Surface (cm)	Silty Clay		Silty Clay Loam		Sandy Loam	
	O ₂ (% Volume of Air)	CO ₂ (% Volume of Air)	O ₂ (% Volume of Air)	CO ₂ (% Volume of Air)	O ₂ (% Volume of Air)	CO ₂ (% Volume of Air)
30	18.2	1.7	19.8	1.0	19.9	0.8
61	16.7	2.8	17.9	3.2	19.4	1.3
91	15.6	3.7	16.8	4.6	19.1	1.5
122	12.3	7.9	16.0	6.2	18.3	2.1
152	8.8	10.6	15.3	7.1	17.9	2.7
183	4.6	10.3	14.8	7.0	17.5	3.0

Source: V. Evangelou, *Environmental Soil and Water Chemistry: Principles and Applications*, John Wiley Sons, Inc., Canada, 1998.

and enlightening cases in decision making in waste management. Scholars and practitioners alike have studied its convoluted history and the critical paths of decisions. The eventual exposures of people to harmful remnant waste constituents event trees was a complicated series of events brought on by military, commercial, and civilian governmental decisions. One particularly interesting event tree is the one that led to the public school district's decision to accept the donation of land and building the school on the property. As regulators and the scientific community learned more, a series of laws were passed and new court decisions and legal precedents established in the realm of toxic substances. Additional hazardous wastes sites began to be identified, which continue to be listed on the EPA website's National Priority Listing. [7] It would behoove managers to become familiar with each cleanup step in [Chapters 8 and 31](#) for handling and treating hazardous wastes, as well as those provided by regulators, for example, the EPA [8].

2 THE GROWTH OF ENVIRONMENTAL REGULATIONS

Waste management must be seen with the context of general environmental awareness, which grew rapidly in the second half of the 20th Century. With this awareness came the public demand for environmental safeguards and remedies to environmental problems was an expectation of a greater role for government. A number of laws were on the books prior to the 1960s, such as early versions of federal legislation to address limited types of water and air pollution, and some solid waste issues, such as the need to eliminate open dumping.

The appreciation for the need for proper waste management also tracked with protection of surface waters. As evidence, at the end of the 19th century, the Rivers and Harbors Act was enacted to authorize the regulation of activities

affecting navigation in United States waters, including wetlands. Indeed, Section 10 of this early legislation highlighted the need to consider "fill" in the waters of the United States, including dredging operations. The dredge and fill permits were later enhanced by Section 404 of the Clean Water Act. Indeed, the dredged sediments themselves became high priority wastes, especially in the Great Lake region and later ocean dumping. The earliest sediment waste chemical criteria were promulgated in 1971, known as the "Jensen Criteria" [9]:

1. Chemical oxygen demand (COD);
2. Total Kjeldahl nitrogen (TKN);
3. Volatile solids;
4. Oil and grease;
5. Mercury;
6. Lead;
7. Zinc.

The tumultuous decade of the 1960s saw the environment as a social cause, akin to the civil rights and antiwar movements. Major public demonstrations on the need to protect "spaceship earth" encouraged elected officials to address environmental problems, exemplified by air pollution "inversions" that capped polluted air in urban valleys, leading to acute diseases and increased mortality from inhalation hazards, the "death" of Erie Canal and rivers catching on fire in Ohio and Oregon. At this time, many began to perceive solid waste generation as a crisis. [10]

2.1 The National Environmental Policy Act

The environmental movement was institutionalized in the United States by a series of new laws and legislative amendments. The National Environmental Policy Act (NEPA) was emblematic of the new federal commitment to environmental stewardship. It was signed into law in 1970 after contentious hearings in the U.S. Congress. [11] NEPA was not really a technical

law. It did two main things. It created the Environmental Impact Statement (EIS) and established the Council on Environmental Quality (CEQ) in the Office of the President. Of the two, the EIS represented a sea change in how the federal government was to conduct business. Agencies were required to prepare EISs on any major action that they were considering that could “significantly” affect the quality of the environment. From the outset, the agencies had to reconcile often competing values, that is, their mission and the protection of the environment.

The CEQ was charged with developing guidance for all federal agencies on NEPA compliance, especially when and how to prepare an EIS. The EIS process combines scientific assessment with public review. The process is similar for most federal agencies. Agencies often strive to receive a so-called FONSI or the finding of no significant impact, so that they may proceed unencumbered on a mission-oriented project. (Note: Pronounced “Fonzy” like that of the nickname for character Arthur Herbert Fonzarelli portrayed by Henry Winkler in the television show, *Happy Days*.)

The Federal Highway Administration’s FONSI process provides an example of the steps needed to obtain a FONSI for a project.

Whether a project either leads to a full EIS or a waiver through the FONSI process, it will have to undergo an evaluation. This step is referred to as an “environmental assessment.” An incomplete or inadequate assessment will lead to delays and increases the chance of an unsuccessful project, so sound science is needed from the outset of the project design.

The final step is the Record of Decision (ROD). The ROD describes the alternatives and the rationale for final selection of the best alternative. It also summarizes the comments received during the public reviews and how the comments were addressed. Many states have adopted similar requirements for their RODs.

The courts adjudicated some very important laws along the way, requiring federal agencies

to take NEPA seriously. Some of the aspects of the “give and take” and evolution of federal agencies’ growing commitment to environmental protection were the acceptance of the need for sound science in assessing environmental conditions and possible impacts, and the very large role of the public in deciding on the environmental worth of a highway, airport, dam, waterworks, treatment plant, or any other major project sponsored by or regulated by the federal government. This was a major impetus in the growth of the environmental disciplines since the 1970s. Experts were called upon, not only to conduct credible scientific assessments, but also who could meaningfully communicate the assessments to the public.

Since virtually any federal activity can have some impact on the environment, all federal agencies must follow the CEQ regulations that require agencies to meet their obligations under NEPA. Thus environmental considerations must accompany economic, social, and other agency priorities. [12]

Agencies are required to identify the major decisions called for by their principal programs and make certain that the NEPA process addresses them. This process must be set up in advance, early in agency’s planning stages. For example, if waste remediation or reclamation is a possible action, the NEPA process must be woven into the remedial action planning processes from beginning with the identification of the need for and possible kinds of actions being considered.

Noncompliance or inadequate compliance with NEPA rules regulations can lead to severe consequences, including lawsuits, increased project costs, delays, and the loss of the public’s loss of trust and confidence, even if the project is designed to improve the environment, and even if the compliance problems seem to be only “procedural.”

The U.S. EPA is responsible for reviewing the environmental effects of all federal agencies’ actions. This authority was written as Section 309

of the Clean Air Act (CAA). The review must be followed with the EPA's public comments on the environmental impacts of any matter related to the duties, responsibilities, and authorities of EPA's administrator, including EISs. The EPA's rating is designed to determine whether a proposed action by a federal agency is unsatisfactory from the standpoint of public health, environmental quality, or public welfare. [13]

The EPA may rate a proposed federal project as LO, lack of objectives; EC, environmental concerns; EO, environmental objections; or EU, environmentally unsatisfactory. The EPA also rates the quality of the draft EIS itself as adequate (1), having insufficient information (2), or inadequate (3). So, for example, a waste management project EIS that is acceptable would be rated LO, one about which EPA has concerns, but which the EIS contains insufficient documentation would be EC-2, and one which is not only is the proposed project environmentally unacceptable, but the EIS also does not adequately assess the impacts would be rated EU-3. There is also a strong possibility that if the EIS is inadequate, it is impossible to gauge the environmental impacts. In this case, the rating would simply be "3."

The passage of NEPA opened the path for a number of new laws to address specific problems in various environmental media. Since this handbook's main focus is waste, we will discuss the waste management laws first, followed by brief overviews of air, water, and consumer protection laws.

3 SOLID AND HAZARDOUS WASTES LEGISLATION

Numerous laws, including those previously mentioned, are directed at wastes, but the two principal U.S. laws governing solid wastes are the Resource Conservation and Recovery Act (RCRA) and Superfund. The RCRA law covers both hazardous and solid wastes, while

Superfund and its amendments generally address abandoned hazardous waste sites. RCRA addresses active hazardous waste sites.

3.1 Management of Active Hazardous Waste Facilities

With RCRA [14] the U.S. EPA received the authority to control hazardous waste throughout the wastes' entire life cycle, known as the "cradle-to-grave." This means that manifests must be prepared to keep track of the waste, including its generation, transportation, treatment, storage, and disposal. RCRA also set forth a framework for the management of nonhazardous wastes in Subtitle D.

The Federal Hazardous and Solid Waste Amendments [15] (HSWA) to RCRA required the phase out of land disposal of hazardous waste. HSWA also increased the federal enforcement authority related to hazardous waste actions, set more stringent hazardous waste management standards, and provided for a comprehensive underground storage tank program.

The 1986 amendments to RCRA allowed the federal government to address potential environmental problems from underground storage tanks (USTs) for petroleum and other hazardous substances.

3.2 Addressing Abandoned Hazardous Wastes

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) is commonly known as Superfund [16]. The U.S. Congress enacted it in 1980 to create a tax on the chemical and petroleum industries and to provide extensive federal authority for responding directly to releases or threatened releases of hazardous substances that may endanger public health or the environment.

The Superfund law established prohibitions and requirements concerning closed and abandoned hazardous waste sites, established

provisions for the liability of persons responsible for releases of hazardous waste at these sites, and established a trust fund to provide for cleanup when no responsible party could be identified.

The CERCLA response actions include:

- Short-term removals, where actions may be taken to address releases or threatened releases requiring prompt response. This is intended to eliminate or reduce exposures to possible contaminants.
- Long-term remedial response actions to reduce or eliminate the hazards and risks associated with releases or threats of releases of hazardous substances that are serious, but not immediately life threatening. These actions can be conducted only at sites listed on EPA's National Priorities List (NPL).

Superfund also revised the National Contingency Plan (NCP), which sets guidelines and procedures required when responding to releases and threatened releases of hazardous substances.

CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) in 1986 [17]. These amendments stressed the importance of permanent remedies and innovative treatment technologies in cleaning up hazardous waste sites. SARA required that Superfund actions consider the standards and requirements found in other State and Federal environmental laws and regulations and provided revised enforcement authorities and new settlement tools. The amendments also increased State involvement in every aspect of the Superfund program, increased the focus on human health problems posed by hazardous waste sites, encouraged more extensive citizen participation in site cleanup decisions, and increased the size of the Superfund trust fund.

SARA also mandated that the Hazard Ranking System (HRS) be revised to make sure of the adequacy of the assessment of the relative degree of risk to human health and the environment posed by uncontrolled hazardous waste

sites that may be placed on the National Priorities List (NPL).

4 CLEAN AIR LEGISLATION

Although solid and hazardous waste laws hold primacy for most waste managers, they must also consider impacts on air quality. Landfills and other bioreactors emit methane and other pollutants to the air; thermal destruction of wastes emit carbon dioxide, aerosols, and products of incomplete combustion; sludge dewatering releases volatile organic compounds, to name a few of the connections between air pollution and solid waste management. The 1970 amendments to the Clean Air Act [18] arguably ushered in the era of environmental legislation with enforceable rules. The 1970 version of the Clean Air Act was enacted to provide a comprehensive set of regulations to control air emissions from area, stationary, and mobile sources. This law authorized the EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and the environment from the so-called criteria pollutants: carbon monoxide (CO), particulate matter, nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and photochemical oxidant smog or ozone. The metal lead (Pb) was later added as the sixth NAAQS pollutant. Strong evidence supported the need to decrease the exposure to these six pollutants to protect public health. The Amendments also addressed so-called hazardous air pollutants (HAPs), but not as general ambient standards, but as limits on emissions from specific source categories.

The Amendments' initial goal was that each state would meet all NAAQS by 1975. Unfortunately, this goal remains unmet. In addition, each was to develop state implementation plans (SIPs) to address industrial sources of the criteria pollutants not in compliance with NAAQS. The ambient atmospheric concentrations are presently measured at over 4000 monitoring sites across the United States. The ambient levels

TABLE 3.3 Percent Change in Air Quality in the United States as Reflected by Trends in the Six National Ambient Air Quality Standard (NAAQS) Pollutants

	1980 vs. 2016	1990 vs. 2016	2000 vs. 2016	2010 vs. 2016
Carbon monoxide	–85	–77	–61	–14
Lead	–99	–99	–93	–77
Nitrogen dioxide (annual)	–62	–56	–47	–20
Nitrogen dioxide (1-h)	–61	–50	–33	–15
Ozone (8-h)	–31	–22	–17	–5
PM ₁₀ (24-h)	–	–39	–40	–9
PM _{2.5} (annual)	–	–	–42	–22
PM _{2.5} (24-h)	–	–	–44	–23
Sulfur dioxide (1-h)	–87	–85	–72	–56

Source: U.S. Environmental Protection Agency Air Quality Trends. <https://www.epa.gov/air-trends/air-quality-national-summary#air-quality-trends> (accessed 23.02.17).

have continuously decreased, as presented in Table 3.3. The state and local agencies and tribal authorizes have numerous ways to comply with SIPs, many of which are described in the Menu of Control Measures (MCM) [19]. The MCM is a spreadsheet that includes emission reduction strategies, plans, and programs and is continuously updated.

The Clean Air Act Amendments of 1977 listed new dates to achieve attainment of NAAQS (many areas of the country had not met the prescribed dates set in 1970). Other amendments were targeted at air pollution, which had been insufficiently addressed, including acidic deposition (so-called acid rain), tropospheric ozone pollution, depletion of the stratospheric ozone layer, and a new program for air toxics, the National Emission Standards for Hazardous Air Pollutants (NESHAPS).

The 1990 Amendments to the Clean Air Act profoundly changed the law, by adding new initiatives and imposing dates to meet the laws new requirements. Here are some of the major provisions.

Cities that failed to achieve human health standards as required by NAAQS were required to reach attainment within 6 years of passage,

although Los Angeles was given 20 years, since it was dealing with major challenges in reducing ozone concentrations.

Almost 100 cities failed to achieve ozone standards and were ranked from *marginal* to *extreme*. The more severe the pollution, the more rigorous controls required, although additional time was given to those extreme cities to achieve the standard. Since ozone is the product of reactions of hydrocarbons and oxides of nitrogen (NO_x) in the presence of light, various measures had to be taken, including new or enhanced automobile inspection/maintenance (I/M) programs, installation of vapor recovery systems at gas stations and other controls of hydrocarbon emissions from small sources, and new transportation controls to offset increases in the number of miles traveled by vehicles. Major stationary sources of NO_x would have to decrease their emissions.

The 41 cities failing to meet CO standards were ranked *moderate* or *serious*; states would have to initiate or upgrade inspection and maintenance programs and adopt transportation controls. The 72 urban areas that did not meet particulate matter (PM₁₀) standards were ranked *moderate*; states will have to implement

Reasonably Available Control Technology (RACT); use of wood stoves and fireplaces may have to be curtailed.

The standards promulgated from the Clean Air Act Amendments are provided in Table 3.4. Note that the new particulate standard addresses smaller particles, that is, particles

with diameters $\leq 2.5\mu\text{m}$ ($\text{PM}_{2.5}$). Research has shown that exposure to these smaller particles is more likely to lead to health problems than do exposures to larger particles. Smaller particles are able to penetrate further into the lungs and hence are probably more bioavailable than the larger PM_{10} .

TABLE 3.4 National Ambient Air Quality Standards (A Discussion on Units is Given as Follows)

Pollutant	Primary/ Secondary	Averaging Time	Level	Form
Carbon monoxide (CO)	Primary	8h	9ppm	Not to be exceeded more than once per year
		1h	35ppm	
Lead (Pb)	Primary and secondary	Rolling 3-month average	$0.15\mu\text{g m}^{-3}$ ^a	Not to be exceeded
Nitrogen dioxide (NO ₂)	Primary	1h	100ppb	98th percentile of 1-h daily maximum concentrations, averaged over 3 years
	Primary and secondary	1 year	53ppb ^b	Annual mean
Ozone (O ₃)	Primary and secondary	8h	0.070ppm^c	Annual fourth-highest daily maximum 8-h concentration, averaged over 3 years
Particle pollution (PM)	PM _{2.5} Primary	1 year	$12.0\mu\text{g m}^{-3}$	Annual mean, averaged over 3 years
	Secondary	1 year	$15.0\mu\text{g m}^{-3}$	Annual mean, averaged over 3 years
	Primary and secondary	24h	$35\mu\text{g m}^{-3}$	98th percentile, averaged over 3 years
	PM ₁₀ Primary and secondary	24h	$150\mu\text{g m}^{-3}$	Not to be exceeded more than once per year on average over 3 years
Sulfur dioxide (SO ₂)	Primary	1h	75ppb ^d	99th percentile of 1-h daily maximum concentrations, averaged over 3 years
	Secondary	3h	0.5ppm	Not to be exceeded more than once per year

^a In areas designated nonattainment for the Pb standards prior to the promulgation of the current (2008) standards, and for which implementation plans to attain or maintain the current (2008) standards have not been submitted and approved, the previous standards ($1.5\mu\text{g m}^{-3}$ as a calendar quarter average) also remain in effect.

^b The level of the annual NO₂ standard is 0.053ppm. It is shown here in terms of ppb for the purposes of clearer comparison to the 1-h standard level.

^c Final rule signed October 1, 2015, and effective December 28, 2015. The previous (2008) O₃ standards additionally remain in effect in some areas.

Revocation of the previous (2008) O₃ standards and transitioning to the current (2015) standards will be addressed in the implementation rule for the current standards.

^d The previous SO₂ standards (0.14ppm 24-h and 0.03ppm annual) will additionally remain in effect in certain areas: (1) any area for which it is not yet 1 year since the effective date of designation under the current (2010) standards, and (2) any area for which an implementation plan providing for attainment of the current (2010) standard has not been submitted and approved and which is designated nonattainment under the previous SO₂ standards or is not meeting the requirements of a SIP call under the previous SO₂ standards (40 CFR 50.4(3)). A SIP call is an EPA action requiring a state to resubmit all or part of its State Implementation Plan to demonstrate attainment of the required NAAQS.

Source: U.S. Environmental Protection Agency NAAQS Table. <https://www.epa.gov/criteria-air-pollutants/naaqs-table> (accessed 27.02.18).

DISCUSSION BOX 3.1 WASTE UNITS

The concentration of gases, vapors, and liquids is often expressed as volume of contaminant in a specific volume of air or water, referred to as volume per unit volume. This is most conveniently expressed as parts per million (ppm) or percent by volume. Parts per million is the volume of contaminant per million volumes of air. Any volume unit can be used as long as the units for both parts are the same (e.g., liters of contaminant per million liters of air or water). Measurements in percent volume are less applicable to hazardous waste characterization because they represent very high concentrations that would not usually be found in environmental contamination situations. Percent by volume can be thought of as parts per hundred, so:

$$(\% \text{ by volume}) \times (1000) = \text{ppm}$$

For liquids, the volume to volume (V:V) concentration can be converted to mass per volume (M:V) concentrations if the density of the concentrated substance and the density of the liquid are known. Many environmental texts and models use short-hand terms of “solvent” and “solute”; however, not all substances of concern are dissolved (e.g., some contaminants are suspended as particles or in emulsions in water). The liquid that we are usually most interested in is water.

For example, we want to know how much of the bad stuff (pollutants) or good stuff (e.g., dissolved oxygen) is in the water. The density of water under most environmental conditions is very nearly unity, so the V:V concentration can be converted to M:V concentration simply as:

$$\text{ppm} = C \times \rho \quad (3.1)$$

where C = concentration of substance in water (mg L^{-1}) and ρ = pollutant density of the substance (g mL^{-1}).

Thus if the M:V concentration is micrograms per liter ($\mu\text{g L}^{-1}$) the V:V concentration will be in parts per billion (ppb); and if the M:V concentration is nanograms per liter (ng L^{-1}) the V:V concentration will be in parts per trillion (ppt).

Converting from V:V to M:V concentrations in air is a bit more complicated than that of water, because gas densities depend upon the gas laws. The gas law states that the product of pressure (P) and the volume occupied by the gas (V) is equal to the product of the number of moles (n), the gas constant (R), and the absolute temperature (T) in degrees Kelvin. That is:

$$PV = nRT \quad (3.2)$$

4.1 Mobile Sources

Vehicular tailpipe emissions of hydrocarbons, CO, and NO_x were to be reduced with the 1994 models. Standards now have to be maintained over a longer vehicle life. Evaporative emission controls were mentioned as a means for reducing hydrocarbons. Beginning in 1992, “oxyfuel” gasolines blended with alcohol began to be sold during winter months in cities with severe CO problems. In 1995 reformulated gasolines with aromatic compounds were introduced in the nine cities with the worst ozone problems, but other cities were allowed to participate. Later, a

pilot program introduced 150,000 low emitting vehicles to California that meet tighter emission limits through a combination of vehicle technology and substitutes for gasoline or blends of substitutes with gasoline. Other states are also participating in this initiative.

4.2 Hazardous Air Pollutants

In contrast with NAAQS, which aim to lower overall ambient concentrations of a small number of air pollutants, Section 112 of the Clean Air Act created the National Emissions Standards for Hazardous Air Pollutants

(NESHAPS), which are intended to decrease emissions of hazardous air pollutants (HAPs). The number of HAPs, commonly known as “air toxics,” was increased to 189 compounds in 1990 (The list now includes 187 HAPs; see Appendix A). Most of these are carcinogenic, mutagenic, and/or toxic to neurological, endocrine, reproductive, and developmental systems. All HAP emissions were to be reduced within 10 years of enactment. The EPA published a list of source categories and the Maximum Achievable Control (MACT) standards for each category over a specified timetable.

The next step beyond MACT standards is to begin to address chronic health risks that would still be expected if the sources meet these standards. This is known as residual risk reduction. The first step was to assess the health risks from air toxics emitted by stationary sources that emit air toxics after technology-based (MACT) standards are in place. The residual risk provision sets additional standards if MACT does not protect public health with Section 112(f) refers to as an “ample margin of safety.” In addition, human health endpoints, other standards can be if needed to prevent adverse environmental effects.

The EPA is responsible for deciding on what steps need to be taken to achieve this factor of safety for any HAP source category where actions to date have not sufficiently protected public health. The exact meaning “ample margin of safety” varies, but it is the difference between the present and desired state of risk posed by the emissions from a HAP source

category. An example of this margin for airborne carcinogens is shown in Fig. 3.4. According to this logic, if a source can demonstrate that it will not contribute to $>10^{-6}$ cancer risk, then it meets the ample margin of safety requirements for air toxics. The targets vary by HAP. For example, in an early NESHAP for benzene, EPA’s margin was defined as providing:

... maximum feasible protection against risks to health from hazardous air pollutants by (1) protecting the greatest number of persons possible to an individual lifetime risk level no higher than approximately 1-in-1 million and (2) limiting to no higher than approximately 1-in-10 thousand [i.e., 100-in-1 million] the estimated risk that a person living near a plant would have if he or she were exposed to the maximum pollutant concentrations for 70 years. [20]

The ample margin can also be used to protect populations from HAPs other than carcinogens, such as neurotoxins, by applying a hazard quotient (HQ). The HQ is the ratio of the potential exposure to the substance and the level at which no adverse effects are expected. An $HQ < 1$ means that the exposure levels to a chemical should not lead to adverse health effects. Conversely, an $HQ > 1$ means that adverse health effects are possible. Due to uncertainties and the feedback that is coming from the business and scientific communities, the ample margin of safety threshold is presently ranging from $HQ = 0.2$ to 1.0. So, if a source can demonstrate that it will not contribute to greater than the threshold (whether it is 0.2, 1.0, or some other

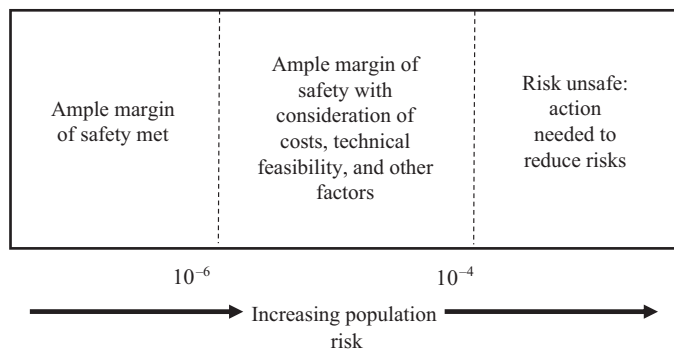


FIG. 3.4 Ample margin of safety to protect public health and adverse environmental effects from an air pollutant. Source: *Clean Air Act Amendments of 1990, Section 112(f)(2)*.

level established by the federal government) for noncancer risk, it meets the ample margin of safety requirements for air toxics.

4.3 Air Pollution Regulations in the UK

In the United Kingdom, air pollution regulations were first directed at the smoke produced by the burning of coal and wood in industries and households and culminated in the Clean Air Acts of 1956 and 1968. (This section is based

on the section in Chapter 3 of the first edition by Trevor Letcher) Over the past 70 years the focus has shifted to chemical pollution from factories and from vehicle emissions. In particular, the 1970s and 1980s saw legislation aimed at SO₂, NO_x and particulates, CO, benzene, and other hydrocarbons pollution, culminating in the National Air Quality Strategies for the UK in 1997 and 2000. The latest Air Quality Standards that came into force on 11 June 2010 is given in [Table 3.5](#). The standard limits have not altered

TABLE 3.5 United Kingdom's Air Quality Standards Regulations 2010/2017

Averaging Period		Limit Value	
Sulfur dioxide			
One hour		350µgm ⁻³ not to be exceeded >24 times a calendar year	
One day		125µgm ⁻³ not to be exceeded >3 times a calendar year	
Nitrogen dioxide			
One hour		200µgm ⁻³ not to be exceeded >18 times a calendar year	
Calendar year		40µgm ⁻³	
Benzene			
Calendar year		5µgm ⁻³	
Lead			
Calendar year		0.5µgm ⁻³	
PM ₁₀			
One day		50µgm ⁻³ , not to be exceeded >35 times a calendar year	
Calendar year		40µgm ⁻³	
Averaging Period	Limit Value	Margin of Tolerance	Date by Which Limit Value is to be Met
PM _{2.5}			
Calendar year	25µgm ⁻³	20% on 11th June 2008, decreasing on the next 1st January and every 12months thereafter by equal annual percentages to reach 0% by 1st January 2015	1st January 2015
Averaging period			Limit value
Carbon monoxide			
Maximum eight hour daily mean ^a			10mgm ⁻³

^a The maximum daily eight-hour mean concentration of carbon monoxide must be selected by examining eight-hour running averages, calculated from hourly data and updated each hour. Each eight-hour average so calculated will be assigned to the day on which it ends, that is, the first calculation period for any one day will be from 17:00 on the previous day to 01:00 on that day, the last calculation period for any one day will be the period from 16:00 to 24:00 on that day.

over the past 8 years (2018). But changes are to take place in the near future as the following report states “This instrument transposes the Directive in the United Kingdom. The instrument requires overall anthropogenic emissions in the United Kingdom for five damaging air pollutants: nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2), ammonia (NH_3) and fine particulate matter ($\text{PM}_{2.5}$) to be reduced below a specified percentage of overall emissions of those which were emitted in the base year (2005). These national emission reduction commitments need to be met in two phases, from 2020 to 2029, with more stringent levels to be met from 2030 onwards.” See reference [21] http://www.legislation.gov.uk/ukxi/2018/129/pdfs/ukxiem_20180129_en.pdf. The UK National Atmospheric Emissions Inventory can be obtained or viewed at the Department for Environment, Food and Rural Affairs, Nobel House, 17 Smith Square, London SW1P 3JR or accessed at [22] <http://naei.beis.gov.uk/data/data-selector?view=air-pollutants>.

In many respects the regulations in the USA and in the UK (and indeed in Europe) relating to waste and pollution have followed similar paths and the laws have been drafted for similar reasons. This is an excellent example of technology transfer and knowledge building.

Other nations have deployed similar rules for both criteria and hazardous air pollutants. Directive 2001/81/EC of European Union (EU), for example, limits total national emissions of sulfur dioxide, nitrogen oxides, volatile organic compounds, and ammonia. [23] These pollutants are of continental scale and are transported across national boundaries. The World Health Organization and other global environmental institutions measure the emissions of various air toxics, such as dioxins, mercury, and hydrogen cyanide. [24]

5 WATER QUALITY LEGISLATION

As is true for air pollution, waste managers are often confronted with the challenge of solving one environmental problem with another. Gathering wastes at a central site like a landfill may solve the problem of litter and refuse, water will be polluted if the landfill released chemicals in its leachate.

Environmental water laws come in two forms: Those aimed at providing “clean water” to drink and use, and those cleaning up “dirty water.” The Safe Drinking Water Act is the principal federal law designed to provide the U.S. population with potable water. The Clean Water Act addresses the many aspects of water pollution.

5.1 Drinking Water

The Safe Drinking Water Act [25] (SDWA) was passed in 1974 to protect public drinking water supplies from harmful contaminants, assuring that the concentrations of these contaminants in drinking water stay below Maximum Contaminant Levels (MCLs). The Act, as amended, authorizes a set of regulatory programs to establish standards and treatment requirements for drinking water, as well as the control underground injection of wastes that may contaminate water supplies, and the protection of groundwater resources.

The SDWA was extensively amended in 1986 to strengthen the standard-setting procedures, increase enforcement authority, and provide for additional groundwater protection programs. The U.S. EPA was mandated to issue drinking water regulations for 83 specified contaminants by 1989 and for 25 additional contaminants every 3 years thereafter (see Appendix B). The 1986 Amendments also required that all public water systems using surface water disinfect, and possibly filter, water supplies. Thus far, EPA has regulated 84 contaminants. The law

covers all public water systems with piped water for to be used for human consumption with at least 15 service connections or a system that regularly serves at least 25 people.

Most serious violations of drinking water regulations have occurred in small water systems serving populations of <3300. This is often the result of limited financial and technical resources that can be devoted to water monitoring and treatment. Because 87% of all community water systems are small, amendments to the SDWA have focused on increasing the abilities of these communities to meet regulatory requirements, known as “capacity building.”

Standards are a balance of costs and risks, including considerations of how and whether to discourage the formation of new drinking water systems that are unlikely to comply, and the appropriate state and federal roles in providing high quality water supplies.

Much of the world lacks centralized water systems. Even highly developed nations have large areas where wells and other residential systems provide most of the rural population’s drinking water. Improper waste disposal at the wellhead or point of use is an important source of drinking water contaminants, both chemical and microbial [26]. The systems are often unmonitored and unregulated, so even if the wellheads were properly maintained, users are vulnerable to upgradient contamination. As indicated in Fig. 3.3, a paramount role of waste managers is to prevent contamination of water supplies by leachate from landfills and other municipal waste facilities [27–29].

5.2 Water Pollution Abatement

The Clean Water Act (CWA), passed in 1972, represents the myriad programs aimed at surface water quality protection in the United States, employing a variety of regulatory and nonregulatory approaches needed to reduce

direct pollutant discharges into U.S. waterways. This has accomplished through the issuance of effluent discharge permits, designation of water quality protection levels for water bodies, financing municipal wastewater treatment facilities, and managing nonpoint sources to allow polluted runoff to enter surface waters. The goal of these actions is to restore and to maintain the chemical, physical, and biological integrity of the nation’s waters so that they can support in the words of the Act, “the protection and propagation of fish, shellfish, and wildlife and recreation in and on the water” [30].

For years after the CWA became law, the major focus of the federal government, states, and Native American tribes was on the chemical aspects of the “integrity” goal cited before. More recently, greater attention has been paid to other provisions of the Act to physical and biological integrity. The implementation of the law has also moved from almost completely focusing on the regulation of pollutant discharges from “point source” facilities, like municipal wastewater treatment plants and industrial facilities, to greater attention now being given to pollution from mining operations, roads, construction sites, farms, and other “nonpoint sources.”

In many ways, nonpoint problems are more intractable than point sources, because they more heavily depend on management and comprehensive planning programs. Some successful nonpoint programs have included voluntary programs, like cost sharing with landowners. So-called wet weather point sources such as urban storm sewer systems and construction sites, require regulatory actions.

The traditional “command and control” programs of enforcement and compliance programs have been evolving into a greater number of programs that consist of comprehensive watershed-based strategies, where more equity exists between the protection of healthy waters and the restoration of impaired surface waters.

Such holistic approaches depend heavily on public involvement and coalition building to achieve water quality objectives that are both technically sound and publicly acceptable.

6 ENVIRONMENTAL PRODUCT AND CONSUMER PROTECTION LAWS

Although most of the authorizing legislation targeted at protecting and improving the environment is based upon actions needed in specific media, that is, air, water, soil, and sediment, some law has been written in an attempt to prevent environmental and public health problems while products are being developed and before their usage.

The predominant product laws designed to protect the environment are the Federal Food, Drug, and Cosmetics Act (FFDCA); the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA); and the Toxic Substances Control Act (TSCA). These three laws look at products in terms of potential risks for yet-to-be-released products and estimated risks for products already in use. If the risks are unacceptable, new products may not be released as formulated or the uses will be strictly limited to applications that meet minimum risk standards. For products already in the marketplace, the risks are periodically reviewed. For example, pesticides have to be periodically reregistered with the government. This reregistration process consists of reviews of new research and information regarding health and environmental impacts discovered since the product's last registration.

FIFRA's major mandate is to control the distribution, sale, and applications of pesticides. This not only includes studying the health and environmental consequences of pesticide usage, but also to require that those applying the pesticides register when they purchase the products. Commercial applicators must be certified by successfully passing exams on the safe use of pesticides. FIFRA requires that the EPA license

any pesticide used in the United States. The licensing and registration makes sure that pesticide is properly labeled and will not cause unreasonable environmental harm.

An important, recent product production law is the Food Protection Act (FQPA), including new provisions to protect children and limit their risks to carcinogens and other toxic substances. The law is actually an amendment to FIFRA and FFDCA that includes new requirements for safety standard-reasonable certainty of no harm that must be applied to all pesticides used on foods. FQPA mandates a single, health-based standard for all pesticides in all foods; gives special protections for infants and children; expedites approval of pesticides likely to be safer than those in use; provides incentives for effective crop protection tools for farmers; and requires regular reevaluation of pesticide registrations and tolerances so that the scientific data supporting pesticide registrations includes current findings.

Another product-related development in recent years is the growth in the importance of screening and prioritizing chemicals for possible harm and exposure prior to their appearance in the marketplace. For example, research suggests a link between exposure to certain chemicals and damage to the endocrine system in humans and wildlife. Because of the potentially serious consequences of human exposure to endocrine disrupting chemicals, the U.S. Congress added specific language on endocrine disruption in the FQPA and recent amendments to SDWA. The FQPA mandated that the EPA develop an endocrine disruptor screening program, and the SDWA authorizes EPA to screen endocrine disruptors found in drinking water systems.

The Endocrine Disruptor Screening Program focuses on methods and procedures to detect and to characterize the endocrine activity of pesticides and other chemicals (see [Fig. 3.5](#)). EPA will use the assays in a two-tiered screening and testing process. Tier 1 identifies chemicals with the potential to interact with the endocrine system. Tier 2 characterizes the

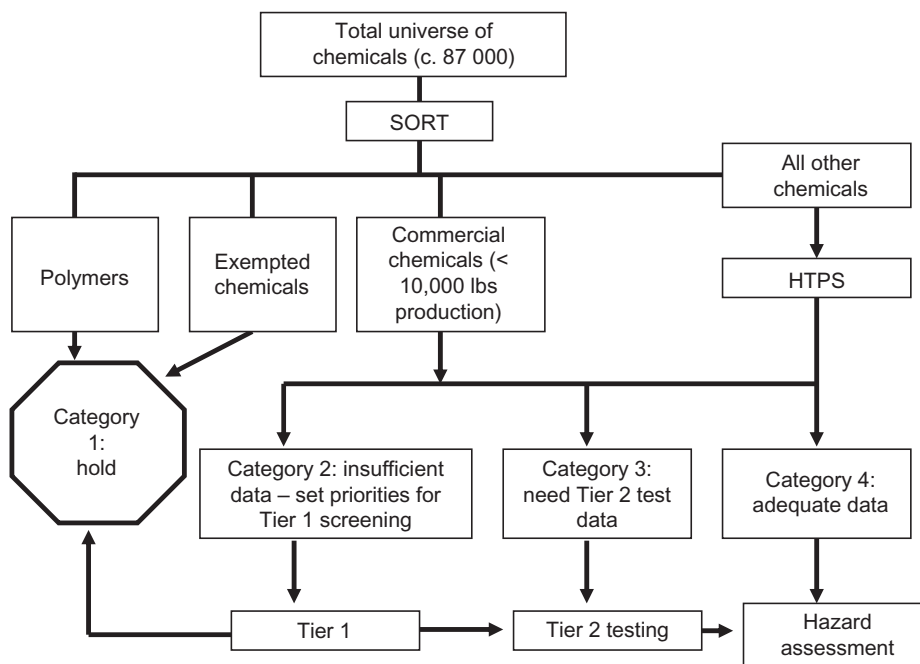


FIG. 3.5 Endocrine Disruptor Screening Program of the U.S. Environmental Protection Agency. Note: HPTS, high throughput prescreening. Sources: E. Protection, *Endocrine Disruptor Screening Program; Policies and Procedures for Initial Screening*; D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Academic Press, 2010.

endocrine-related effects caused by each chemical and obtains information about effects at various doses [31, 32].

The scientific data needed for the estimated 87,000 chemicals in commerce does not exist to conduct adequate assessments of potential risks. The screening program is being used by EPA to collect this information for endocrine disruptors and to decide appropriate regulatory action by first assigning each chemical to an endocrine disruption category:

Chemicals will undergo sorting into four categories according to the available existing, scientifically relevant information:

- Category 1 chemicals have sufficient, scientifically relevant information to determine that they are not likely to interact with the estrogen, androgen, or thyroid systems. This category includes some polymers and certain exempted chemicals.
- Category 2 chemicals have insufficient information to determine whether they are likely to interact with the estrogen, androgen, or thyroid systems, thus will need screening data.
- Category 3 chemicals have sufficient screening data to indicate endocrine activity, but data to characterize actual effects are inadequate and will need testing.
- Category 4 chemicals for already have sufficient data for the EPA to perform a hazard assessment.

TSCA gives the EPA the authority to track thousands of industrial chemicals currently produced or imported into the United States. This is accomplished through screening of the chemicals and requiring that reporting and testing be done for any substance that presents a hazard to human health or the environment. If chemical poses a potential or actual risk that is

unreasonable, the EPA may ban the manufacture and import of that chemical.

The EPA tracks thousands of new chemicals being developed by industries each year, if those chemicals have either unknown or dangerous characteristics. This information is used to determine the type of control that would be needed to protect human health and the environment from these chemicals. Manufacturers and importers of chemical substances first submit information about chemical substances already on the market during an initial inventory. Since the initial inventory was published, commercial manufacturers or importers of substances not on the inventory have been subsequently required to submit notices to the EPA, which has developed guidance about how to identify chemical substances to assign a unique and unambiguous description of each substance for the inventory. The categories include:

- Polymeric substances;
- Certain chemical substances containing varying carbon chain;
- Products containing two or more substances, formulated and statutory mixtures; and
- Chemical substances of unknown or variable composition, complex reaction products and biological materials (UVCB substance).

The product laws are likely to be changed soon. In fact, the European Commission and individual nations are strengthening their methods for screening and prioritizing chemicals based on precautions before and after these substances enter the marketplace. The United States is also looking to reauthorize TSCA to improve these safeguards.

7 WASTE REGULATIONS IN UNITED KINGDOM

Waste Management Regulations have been on the statute books in the UK since 1848 with the Public Health Act. This was followed by various amendments to the Public Health Act,

which were precipitated by waste problems such as burning rubbish (paper, wood, etc.) to generate electricity (1874), smoke abatement and scavenging (1875), the urgent need for refuse collection with charges levied (1907), and uncontrolled dumping (1936). Some of this related to dust and cinders from the burning of coal. In 1892 it has been estimated that over 80% by mass of waste was dust and cinders. Today plastic is the most common waste type with 37% by mass.

During the world wars waste regulations were not considered a great priority. In 1947 the Town and Country Planning Act gave local authorities powers to control waste and this postwar period was dominated by the construction of landfills which in many cases developed into tips. Increased smog in cities, as a result of burning coal precipitated the Clean Air Act of 1956, which led to a decrease of open fires in homes and the acceleration of central heating fueled by electricity, oil, or gas. This had a major effect on the composition of household waste which for the next few decades was dominated by food and paper waste.

The Clean Air Act of 1956 made the public more aware of chemical waste and pollution. In the 1970s, numerous new waste regulations were launched in light of the new types of chemical waste resulting from the rapid expansion of the plastics industry, new health and safety guidelines, and the developments in the United States (e.g., the previously mentioned Love Canal site). Another catalyst was the discovery in 1971 of a number of metal drums of cyanide that had been dumped at a disused brick kiln at Nuneaton. This led to a huge public outcry, a report by the Royal Commission on Toxic Wastes, and the drafting of the first-ever legislation on the control of hazardous waste. As a result, the Deposit of Poisonous Waste Act of 1972 was drafted in ten days and passed through Parliament over the following month. Also in 1971 the Bristol Friends of the Earth launched their first campaign against nonreturnable bottles and returned thousands of bottles at

Schweppes local headquarters. However, it was not till 1977 that the first bottle banks appeared in Britain. In 1974 the increasing concern over waste disposal led to the Control of Pollution Act of 1974 which regulated the disposal of waste and the disposal sites and began a serious tightening up of ways of disposing of waste.

In 1986 the Single European Act (SEA) added new momentum to European integration and expanded Community powers in a number of fields including environmental issues such as waste and pollution. This sea change influenced many British regulations and in 1990 the British Government produced a white paper on the environment entitled "This Common Inheritance," setting out a strategy of waste minimization and recycling and set a target of 25% for recycling household waste by 2000 (later toned down and amended). This was followed by the Environmental Protection Act of 1990 with more regulations and controls and includes the transition from the Control of Pollution Act 1974 to the new Act. Another European Union Directive (in 1994) introduced the concept of Producer Responsibility with respect to packaging and required member states to set targets on the reduction and recovery of packaging waste. This was followed by a UK regulation entitled Producer Responsibility Obligations which has been amended many times since then (in 1997 the amendment required companies to recover and recycle 38% of their packaging and in 2001 this was increased to 56%). A landfill tax was introduced 2 years later (a tax of £7 per tonne was levied on active waste going into landfills; this was raised every few years and by 2010 it had risen to £48 per tonne). One of the aims was to encourage recycling. In 2000 as befits a millennium celebration, the "Waste Strategy 2000" was published and included revised targets for recycling or composting of household waste: 25% by 2005 and 33% by 2015.

Since then, new or amended regulations have appeared every year relating to issues such as Waste Electrical and Electronic Equipment (WEEE) (see [Chapter 25](#)) the ozone and the

restriction on the manufacture and use fluorocarbons, hazardous waste (see [Chapter 31](#)), restricted hazardous waste, low level radiation disposal, environmental permits, landfill tax, landfill regulations and recently a battery directive which imposes new obligations and rules on the producers, suppliers, and the disposal of batteries (see [Chapters 17 and 25](#)). Other obligations included new limits on the amount of mercury and cadmium in batteries, a ban on disposing of batteries in landfills, and the introduction of a new collection regime for batteries. This surge of regulations is not unlike the situation in the United States described so well in [Fig. 3.1](#). As always the regulations reflect the public's interest and this in turn has been whetted by the ever increasing amount of data being produced by monitoring organizations using analytical tools and equipment which seem to improve their levels of sophistication, detection, and precision almost every year. The standards governing air quality reflect this.

7.1 Global Connections

Waste management must be viewed systematically. In fact, wastes tend to be transported and can cause problems well beyond the borders of nations. One of the key waste management challenges of the 21st century is the ease at which waste problems are simply transferred to countries with less stringent controls.

An illustrative example took place in 1992, when the U.S.-based Gaston Copper Recycling Corporation transported 1000t of dust laden with cadmium and lead to a South Carolina fertilizer manufacturer, Stoller Chemical.³⁶ The fertilizer was made from dust collected from air pollution removal equipment, that is, fabric filters. (NOTE: Air pollution controls, employing fabric filters, (also known as "baghouses") remove particles from the air stream by passing the air through a porous fabric. The fabric filter is efficient at removing fine particles and can exceed efficiencies of 99%. That is, the amount (mass) of particles exiting the unit is 99% less than that entering the

unit. The bag filter is more than mere “sieving” but actually captures particles via diffusion, interception, and inertial impaction, whereas a cyclone generally is based on inertia.)

The company then mixed some of the waste product with fertilizer and then exported 1.5 t of the mixture to Australia and Bangladesh. Such substances require specific manifests and must be permitted in compliance with the Resource Conservation and Recovery Act, in addition to notifying the EPA, as specified by TSCA. The export was even more complicated in that a broker, Hy-Tex Marketing, helped to implement the export.

Bangladesh, as is the case for many developing nations, lacks impoundment laws against waste imports. Thus the shipment was not inspected at entry. In this case, the U.S. Department of Justice indicted the companies in 1992; however, the product remained in Bangladesh. The U.S. Embassy in Bangladesh released a warning in late 1992. Sadly, as reported by the environmental group, Greenpeace, that most of the waste fertilizer sent to Bangladesh was already been distributed throughout Bangladeshi farms by October of 1992. Meanwhile, the Bangladesh government is reported to have halted the transport of the remaining copper and lead-laden fertilizer and set up an investigative commission. Environmental groups in both countries continued to demand that the fertilizer be returned to the United States and the Bangladesh Embassy has officially acknowledged the potential risks to Bangladeshis.

The interconnections of wastes can lead to a “circle of poisons,” the phenomenon where nations may ban a substance, but it continues to be produced and used in other, usually less economically developed, countries. In spite of the ban within the borders of certain countries, the feared substance returns. Thus the rationale for the ban, that is, reduced risks to that country’s inhabitants, is forgone and people continue to be exposed when they import the products that contain or are contaminated with the banned substances.

8 CONCLUSIONS

Managing wastes is a complex challenge throughout the world. Thus the measures discussed in this chapter combined with those in [Chapter 2](#) are necessary. That is, risk management requires the use of numerous tools, including green technologies, waste reduction, strategies regulation, the marketplace, consumer education, and multinational cooperation.

A APPENDIX

Toxic Compounds Listed in the 1990 Clean Air Act Amendments.

CAS #	Chemical or Class
75070	Acetaldehyde
60355	Acetamide
75058	Acetonitrile
98862	Acetophenone
53963	2-Acetylaminofluorene
107028	Acrolein
79061	Acrylamide
79107	Acrylic acid
107131	Acrylonitrile
8107051	Allyl chloride
92671	4-Aminobiphenyl
62533	Aniline
90040	o-Anisidine
1332214	Asbestos
71432	Benzene (including from gasoline)
92875	Benzidine
98077	Benzotrichloride
100447	Benzyl chloride
92524	Biphenyl
117817	Bis (2-ethylhexyl) phthalate (DEHP)
542881	Bis(chloromethyl) ether
75252	Bromoform
106990	1,3-Butadiene
156627	Calcium cyanamide
105602	Caprolactam
133062	Captan
63252	Carbaryl
75150	Carbon disulfide
56235	Carbon tetrachloride

463581	Carbonyl sulfide	122667	1,2-Diphenylhydrazine
120809	Catechol	106898	Epichlorohydrin (1-Chloro-2,3-epoxypropane)
133904	Chloramben	106887	1,2-Epoxybutane
57749	Chlordane	140885	Ethyl acrylate
7782505	Chlorine	100414	Ethyl benzene
79118	Chloroacetic acid	51796	Ethyl carbamate (Urethane)
532274	2-Chloroacetophenone	75003	Ethyl chloride (Chloroethane)
108907	Chlorobenzene	106934	Ethylene dibromide (Dibromoethane)
510156	Chlorobenzilate	107062	Ethylene dichloride (1,2-Dichloroethane)
67663	Chloroform	107211	Ethylene glycol
107302	Chloromethyl methyl ether	151564	Ethyleneimine (Aziridine)
126998	Chloroprene	75218	Ethylene oxide
19773	Cresols/Cresylic acid (isomers and mixture)	96457	Ethylene thiourea
95487	o-Cresol	75343	Ethylidene dichloride (1,1-Dichloroethane)
108394	m-Cresol	50000	Formaldehyde
106445	p-Cresol	76448	Heptachlor
98828	Cumene	118741	Hexachlorobenzene
94757	2,4-D, salts and esters	87683	Hexachlorobutadiene
3547044	DDE	77474	Hexachlorocyclopentadiene
334883	Diazomethane	67721	Hexachloroethane
132649	Dibenzofurans	822060	Hexamethylene-1,6-diisocyanate
96128	1,2-Dibromo-3-chloropropane	680319	Hexamethylphosphoramide
84742	Dibutylphthalate	110543	Hexane
106467	1,4-Dichlorobenzene(p)	302012	Hydrazine
91941	3,3'-Dichlorobenzidene	7647010	Hydrochloric acid
111444	Dichloroethyl ether (Bis(2chloroethyl) ether)	7664393	Hydrogen fluoride (Hydrofluoric acid)
542756	1,3-Dichloropropene	123319	Hydroquinone
62737	Dichlorvos	78591	Isophorone
111422	Diethanolamine	58899	Lindane (all isomers)
121697	N,N-Diethyl aniline (N,N-Dimethylaniline)	108316	Maleic anhydride
64675	Diethyl sulfate	67561	Methanol
119904	3,3-Dimethoxybenzidine	72435	Methoxychlor
60117	Dimethyl aminoazobenzene	74839	Methyl bromide (Bromomethane)
119937	3,3-Dimethylbenzidine	74873	Methyl chloride (Chloromethane)
79447	Dimethyl carbamoyl chloride	71556	Methyl chloroform (1,1,1-Trichloroethane)
68122	Dimethyl formamide	78933	Methyl ethyl ketone (2-Butanone)
57147	1,1 Dimethylhydrazine	60344	Methyl hydrazine
131113	Dimethyl phthalate	74884	Methyl iodide (Iodomethane)
77781	Dimethyl sulfate	108101	Methyl isobutyl ketone (Hexone)
534521	4,6-Dinitro-o-cresol, and salts	624839	Methyl isocyanate
51285	2,4-Dinitrophenol	80626	Methyl methacrylate
121142	2,4-Dinitrotoluene	1634044	Methyl <i>tert</i> butyl ether
123911	1,4-Dioxane (1,4-Diethyleneoxide)		

101144	4,4-Methylene bis (2-chloroaniline)	120821	1,2,4-Trichlorobenzene
75092	Methylene chloride (Dichloromethane)	79005	1,1,2-Trichloroethane
101688	Methylene diphenyl diisocyanate (MDI)	79016	Trichloroethylene
101779	4,4'-Methylenedianiline	95954	2,4,5-Trichlorophenol
91203	Naphthalene	88062	2,4,6-Trichlorophenol
98953	Nitrobenzene	121448	Triethylamine
92933	4-Nitrobiphenyl	1582098	Trifluralin
100027	4-Nitrophenol	540841	2,2,4-Trimethylpentane
79469	2-Nitropropane	108054	Vinyl acetate
684935	N-Nitroso-N-methylurea	593602	Vinyl bromide
62759	N-Nitrosodimethylamine	75014	Vinyl chloride
59892	N-Nitrosomorpholine	75354	Vinylidene chloride (1,1-Dichloroethylene)
56382	Parathion	1330207	Xylenes (isomers and mixture)
82688	Pentachloronitrobenzene (Quintobenzene)	95476	o-Xylenes
87865	Pentachlorophenol	108383	m-Xylenes
108952	Phenol	106423	p-Xylenes
106503	p-Phenylenediamine	NA	Antimony compounds
75445	Phosgene	NA	Arsenic compounds (inorganic, including arsine)
7803512	Phosphine	NA	Beryllium compounds
7723140	Phosphorus	NA	Cadmium compounds
85449	Phthalic anhydride	NA	Chromium compounds
1336363	Polychlorinated biphenyls (Aroclors)	NA	Cobalt compounds
1120714	1,3-Propane sultone	NA	Coke oven emissions
57578	beta-Propiolactone	NA	Cyanide compounds ^a
123386	Propionaldehyde	NA	Glycol ethers ^b
114261	Propoxur (Baygon)	NA	Lead compounds
78875	Propylene dichloride (1,2-Dichloropropane)	NA	Manganese compounds
75569	Propylene oxide	NA	Mercury compounds
75558	1,2-Propylenimine (2-Methyl aziridine)	NA	Mineral fibers ^c
91225	Quinoline	NA	Nickel compounds
106514	Quinone	NA	Polycyclic organic matter ^d
100425	Styrene	NA	Radionuclides (including radon) ^e
96093	Styrene oxide	NA	Selenium compounds
1746016	2,3,7,8-Tetrachlorodibenzo-p-dioxin		
79345	1,1,2,2-Tetrachloroethane		
127184	Tetrachloroethylene (Perchloroethylene)		
7550450	Titanium tetrachloride		
108883	Toluene		
95807	2,4-Toluene diamine		
584849	2,4-Toluene diisocyanate		
95534	o-Toluidine		
8001352	Toxaphene (chlorinated camphene)		

For modifications to this list, visit: <http://www.epa.gov/ttn/atw/pollutants/atwsmod.html> (accessed on February 27, 2018). To date, the modifications have included methyl ethyl ketone, glycol esters, caprolactam, and hydrogen sulfide. A Joint Resolution to remove hydrogen sulfide, which was inadvertently included in the original Section 112(b)(1) list, was passed by the Senate on August 1, 1991 (Congressional Record page S11799), and the House of Representatives on November 25, 1991 (Congressional Record pages H11217-H11219). The Joint Resolution was approved by the President on December 4, 1991. Hydrogen Sulfide is included in Section 112(r) and is subject to the accidental release provisions. For all listings before that contain the word "compounds" and for glycol ethers, the following applies: unless otherwise specified, these listings are defined as including any unique chemical

substance that contains the named chemical (i.e., antimony, arsenic, etc.) as part of that chemical's infrastructure.

^a X'CN where X = H' or any other group where a formal dissociation may occur. For example, KCN or Ca(CN)₂.

^b Includes mono- and di-ethers of ethylene glycol, diethylene glycol, and triethylene glycol R-(OCH₂CH₂)_n-OR' where n = 1, 2, or 3; R = alkyl or aryl groups; R' = R, H, or groups which, when removed, yield glycol ethers with the structure: R-(OCH₂CH₂)_n-OH. Polymers are excluded from the glycol category (see previous note regarding modification).

^c Includes glass, rock, or slag fibers (or other mineral derived fibers) of average diameter 1 μm or less.

^d Includes organic compounds with more than one benzene ring and which have a boiling point greater than or equal to 100°C.

^e A type of atom which spontaneously undergoes radioactive decay.

B APPENDIX

U.S. National Primary Drinking Water Regulations. Source: U.S. Environmental Protection Agency National Primary Drinking Water Regulations. <https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations> (accessed 27.02.18).

Disinfection by-products

Units are in milligrams per liter (mg L⁻¹) unless otherwise noted. Milligrams per liter are equivalent to parts per million (PPM).

Microorganisms

Contaminant	MCLG	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
<i>Cryptosporidium</i>	Zero	TT ^a	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
<i>Giardia lamblia</i>	Zero	TT ^a	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Heterotrophic plate count (HPC)	n/a	TT ^a	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is	HPC measures a range of bacteria that are naturally present in the environment
<i>Legionella</i>	Zero	TT ^a	Legionnaire's disease, a type of pneumonia	Found naturally in water; multiplies in heating systems
Total Coliforms (including fecal coliform and <i>Escherichia coli</i>)	Zero	5.0% ^b	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present ^c	Coliforms are naturally present in the environment; as well as feces; fecal coliforms and <i>E. coli</i> only come from human and animal fecal waste
Turbidity	n/a	TT ^a	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (such as whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites, and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff
Viruses (enteric)	Zero	TT ^a	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste

Contaminant	MCLG ¹	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)	Sources of Contaminant in Drinking Water
Bromate	Zero	0.010	Increased risk of cancer	By-product of drinking water disinfection
Chlorite	0.8	1.0	Anemia; infants and young children: nervous system effects	By-product of drinking water disinfection
Haloacetic acids (HAA5)	n/a ^d	0.060	Increased risk of cancer	By-product of drinking water disinfection
Total trihalomethanes (TTHMs)	-> n/a ^d	====-> 0.080	Liver, kidney, or central nervous system problems; increased risk of cancer	By-product of drinking water disinfection

Disinfectants

Contaminant	MCLG	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Chloramines (as Cl ₂)	MRDLG=4	MRDL=4.0	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes
Chlorine (as Cl ₂)	MRDLG=4	MRDL=4.0	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chlorine dioxide (as ClO ₂)	MRDLG=0.8	MRDL=0.8	Anemia; infants and young children: nervous system effects	Water additive used to control microbes

Inorganic Chemicals

Units are in milligrams per liter (mgL⁻¹) unless otherwise noted. Milligrams per liter are equivalent to parts per million (PPM).

Contaminant	MCLG	MCL or TT	Potential Health Effects From Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Antimony	0.006	0.006	Increase in blood cholesterol; decrease in blood sugar	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder
Arsenic	0	0.010 as of 01/23/06	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass and electronics production wastes

- Quick reference guide
- Consumer fact sheet

Contaminant	MCLG	MCL or TT	Potential Health Effects From Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Asbestos (fiber >10µm)	7 million fibers per liter (MFL)	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Barium	2	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits
Beryllium	0.004	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries
Cadmium	0.005	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints
Chromium (total)	0.1	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits
Copper	1.3	TT ^e ; Action Level=1.3	Short-term exposure: Gastrointestinal distress Long-term exposure: Liver or kidney damage People with Wilson's Disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits
Cyanide (as free cyanide)	0.2	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories
Fluoride	4.0	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	Zero	TT ^e ; Action Level=0.015	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits

Continued

Contaminant	MCLG	MCL or TT	Potential Health Effects From Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Mercury (inorganic)	0.002	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands
Nitrate (measured as Nitrogen)	10	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaking from septic tanks, sewage; erosion of natural deposits
Nitrite (measured as Nitrogen)	1	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaking from septic tanks, sewage; erosion of natural deposits
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines
Thallium	0.0005	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories

Organic Chemicals

Units are in milligrams per liter (mgL^{-1}) unless otherwise noted. Milligrams per liter are equivalent to parts per million (PPM).

Contaminant	MCLG	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Acrylamide	Zero	TT ^f	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment
Alachlor	Zero	0.002	Eye, liver, kidney, or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops

Contaminant	MCLG	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Benzene	Zero	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills
Benzo(a)pyrene (PAHs)	Zero	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines
Carbofuran	0.04	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa
Carbon tetrachloride	Zero	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities
Chlordane	Zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
Chlorobenzene	0.1	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dalapon	0.2	0.2	Minor kidney changes	Runoff from herbicide used on rights of way
1,2-Dibromo-3-chloropropane (DBCP)	Zero	0.0002	Reproductive difficulties; increased risk of cancer	Runoff L ⁻¹ leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards
o-Dichlorobenzene	0.6	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories
p-Dichlorobenzene	0.075	0.075	Anemia; liver, kidney, or spleen damage; changes in blood	Discharge from industrial chemical factories
1,2-Dichloroethane	Zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
1,1-Dichloroethylene	0.007	0.007	Liver problems	Discharge from industrial chemical factories
cis-1,2-Dichloroethylene	0.07	0.07	Liver problems	Discharge from industrial chemical factories
trans-1,2-Dichloroethylene	0.1	0.1	Liver problems	Discharge from industrial chemical factories
Dichloromethane	Zero	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories
1,2-Dichloropropane	Zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories

Continued

Contaminant	MCLG	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Di(2-ethylhexyl) adipate	0.4	0.4	Weight loss, liver problems, or possible reproductive difficulties.	Discharge from chemical factories
Di(2-ethylhexyl) phthalate	Zero	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables
Dioxin (2,3,7,8-TCDD)	Zero	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Endrin	0.002	0.002	Liver problems	Residue of banned insecticide
Epichlorohydrin	Zero	TT ^f	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals
Ethylbenzene	0.7	0.7	Liver or kidneys problems	Discharge from petroleum refineries
Ethylene dibromide	Zero	0.00005	Problems with liver, stomach, reproductive system, or kidneys; increased risk of cancer	Discharge from petroleum refineries
Glyphosate	0.7	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use
Heptachlor	Zero	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide	Zero	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor
Hexachlorobenzene	Zero	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories
Hexachlorocyclopentadiene	0.05	0.05	Kidney or stomach problems	Discharge from chemical factories
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff L ⁻¹ eaching from insecticide used on cattle, lumber, gardens
Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff L ⁻¹ eaching from insecticide used on fruits, vegetables, alfalfa, livestock

Contaminant	MCLG	MCL or TT	Potential Health Effects from Long-Term Exposure Above the MCL (Unless Specified as Short-Term)	Sources of Contaminant in Drinking Water
Oxamyl (Vydate)	0.2	0.2	Slight nervous system effects	Runoff L ⁻¹ leaching from insecticide used on apples, potatoes, and tomatoes
Polychlorinated biphenyls (PCBs)	Zero	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals
Pentachlorophenol	Zero	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories
Picloram	0.5	0.5	Liver problems	Herbicide runoff
Simazine	0.004	0.004	Problems with blood	Herbicide runoff
Styrene	0.1	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills
Tetrachloroethylene	Zero	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners
Toluene	1	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories
Toxaphene	Zero	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff L ⁻¹ leaching from insecticide used on cotton and cattle
2,4,5-TP (Silvex)	0.05	0.05	Liver problems	Residue of banned herbicide
1,2,4-Trichlorobenzene	0.07	0.07	Changes in adrenal glands	Discharge from textile finishing factories
1,1,1-Trichloroethane	0.20	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories
1,1,2-Trichloroethane	0.003	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories
Trichloroethylene	Zero	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories
Vinyl chloride	Zero	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories

Radionuclides

Contaminant	MCLG	MCL or TT	Potential Health Effects From Long-Term Exposure Above the MCL (unless specified as short-term)	Sources of Contaminant in Drinking Water
Alpha particles	None ^e – zero	15 picocuries per Liter (pCi L ⁻¹)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit a form of radiation known as alpha radiation
Beta particles and photon emitters	None ^e – zero	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation
Radium 226 and Radium 228 (combined)	None ^e – zero	5 pCi L ⁻¹	Increased risk of cancer	Erosion of natural deposits
Uranium	Zero	30 µg L ⁻¹ as of 12/08/03	Increased risk of cancer, kidney toxicity	Erosion of natural deposits

Note: MCLG, maximum contaminant level goal; MCL, maximum contaminant level; MRDL, maximum residual disinfectant level; MRDLG, maximum residual disinfectant level goal; TT, treatment technique.

Definitions:

- Maximum contaminant level goal (MCLG)—The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are nonenforceable public health goals.
- Maximum contaminant level (MCL)—The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.
- Maximum residual disinfectant level goal (MRDLG)—The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.
- Treatment technique (TT)—A required process intended to reduce the level of a contaminant in drinking water.
- Maximum residual disinfectant level (MRDL)—The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.

^a EPA's surface water treatment rules require systems using surface water or ground water under the direct influence of surface water to

a. Disinfect their water, and

b. Filter their water, or

c. Meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

- *Cryptosporidium*: Unfiltered systems are required to include *Cryptosporidium* in their existing watershed control provisions
- *G. lamblia*: 99.9% removal/inactivation.
- Viruses: 99.99% removal/inactivation.
- *Legionella*: No limit, but EPA believes that if *Giardia* and viruses are removed/inactivated, according to the treatment techniques in the Surface Water Treatment Rule, *Legionella* will also be controlled.
- Turbidity: For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95% of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs.
- Heterotrophic Plate Count (HPC): No >500 bacterial colonies per milliliter.
- Long Term 1 Enhanced Surface Water Treatment: Surface water systems or groundwater under the direct influence (GWUDI) systems serving fewer than 10,000 people must comply with the applicable Long Term 1 Enhanced Surface Water Treatment Rule provisions (such as turbidity standards, individual filter monitoring, *Cryptosporidium* removal requirements, updated watershed control requirements for unfiltered systems).
- Long Term 2 Enhanced Surface Water Treatment Rule: This rule applies to all surface water systems or ground water systems under the direct influence of surface water. The rule targets additional *Cryptosporidium* treatment requirements for higher risk systems and includes provisions

to reduce risks from uncovered finished water storage facilities and to ensure that the systems maintain microbial protection as they take steps to reduce the formation of disinfection by-products.

• Filter Backwash Recycling: This rule requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state.

^b No >5.0% samples total coliform-positive (TC-positive) in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-positive samples, and one is also positive for *E. coli* fecal coliforms, system has an acute MCL violation.

^c Fecal coliform and *E. coli* are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.

^d Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

• Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg L^{-1}); chloroform (0.07 mg L^{-1}).
• Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.02 mg L^{-1}); monochloroacetic acid (0.07 mg L^{-1}). Bromoacetic acid and dibromoacetic acid are regulated with this group but have no MCLGs.

^e Lead and copper are regulated by a treatment technique that requires systems to control the corrosiveness of their water. If >10% of tap water samples exceed the action level, water systems must take additional steps. For copper, the action level is 1.3 mg L^{-1} , and for lead is 0.015 mg L^{-1} .

^f Each water system must certify, in writing, to the state (using third-party or manufacturer's certification) that when acrylamide and epichlorohydrin are used to treat water, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:

• Acrylamide = 0.05% dosed at 1 mg L^{-1} (or equivalent)
• Epichlorohydrin = 0.01% dosed at 20 mg L^{-1} (or equivalent)

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Waste Collection

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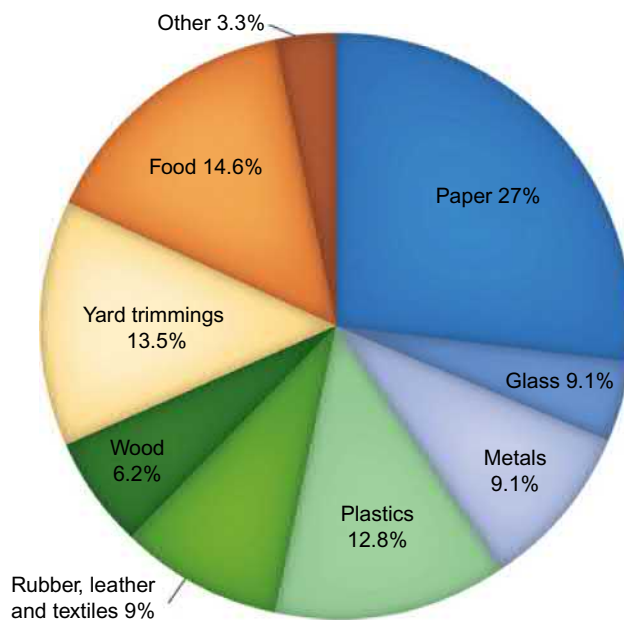
1 INTRODUCTION

This chapter is an update of the chapter of the same title by Fraser McLeod and Tom Cherrett in the first edition of this book. As Fraser McLeod and Tom Cherrett no longer work in this area, coeditor Dan Vallero updated and expanded this chapter.

As the preceding chapters of this book have discussed, there are many different types and sources of waste, ranging from household

garbage to debris found in outer space. This chapter updates the waste collection systems discussed in the first edition [1] by focusing on municipal solid waste (MSW). The types of materials found in MSW are diverse, consisting of wastes from households, streets, parks, schools, hospitals, and some commercial businesses. By weight, the amount of MSW generated is small compared to construction, demolition, manufacture, mining, quarrying, and other industrial sources (See Fig. 4.1). However,

FIG. 4.1 Waste collected in England by sector by weight. Courtesy of U.S. Environmental Protection Agency, *Municipal Solid Waste*, 2018. Available from: <https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/>. (Accessed 16 February 2018).



MSW poses a major problem for the public and its officials. It is the most widespread and general waste collection problem faced by collection authorities the world over. The types of materials range from highly biodegradable, but often putrid substances of biological origin, for example, food waste, to organic substances resistant to biodegradation, for example, plastics, to inorganic, nonbiodegradable substances like metals and glass. Each type poses unique environmental challenges.

Addressing the problems posed by MSW requires a systematic approach that integrates and optimizes collection, transport, storage, and treatment technologies to fit the needs of the local jurisdictions [2]. Both the needs and the technologies matched to these needs have changed substantially in recent years. At the beginning of this century, most MSW was transported, stored, and treated in landfills. In Europe, this has changed substantially with much of the waste now being recycled and composted (See Fig. 4.2).

The extent to which commercial waste is counted as municipal waste varies from country to country, so care must be taken when comparing. For example, throughout most of Europe, commercial and industrial waste from small businesses, which is similar in composition to household waste, is included in the definition of municipal waste [3]. The United Kingdom did not apply this definition before 2011. “Municipal waste” referred to any waste collected by local governments, but the term did not include a substantial proportion of waste similar in nature and composition to household waste generated by businesses and not collected by local governments [4]. The United Kingdom amended its definition in 2011, so that the term now includes these types [5].

The U.S. Environmental Protection Agency (EPA) estimates that residences generate 55%–65% of MSW (See Table 4.1). As the level of detail increases, the range of values increases. The ranges are sufficiently wide that the EPA recommends their waste source be used with caution

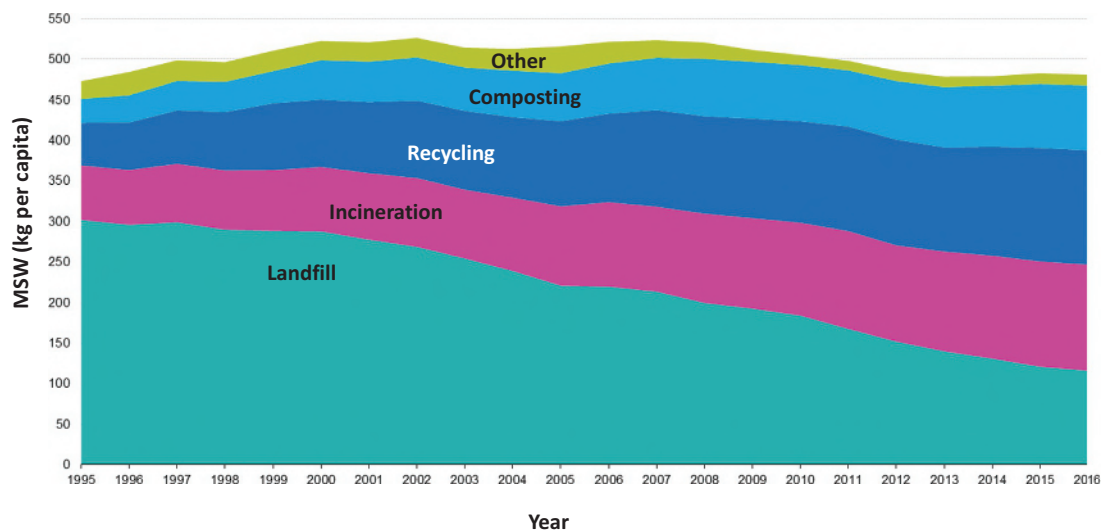


FIG. 4.2 Municipal solid waste treatment technologies in Europe from 1995 to 2016 (kg per capita). Data from European Union, Eurostat, *Statistics Explained: Municipal Waste Statistics*, 2016.

and that they are insufficient to serve as a single residential/commercial allocation data set. Residential and commercial waste appear similar for the states presented in Table 4.1, that is, discards from the residential sector average 51% and commercial sector MSW discards average 49%. The range of discards is 41%–62% for residential sector and 38%–59% for commercial sector MSW. On average, residential sector generation is 46% and commercial sector generation is 54%. The ranges are 39%–54% for residential sector and 46%–61% for commercial sector MSW. However, in 1998, EPAs estimated 55%–65% for residential sector and 35%–45% for commercial sector MSW. Thus the sector contribution to MSW switches, depending on whether discards or generation data are used [6].

The caution on data use extends worldwide, since data are reported differently by jurisdictions. Some define MSW more broadly than others, for example, whether to include construction and other types of waste with the definition of MSW. For example, Germany

generates a net of between 325 and 350 million tonnes of waste are produced annually. Construction and demolition waste account for 60% of this, whereas traditional municipal sources account for only 14%, of which 5% is hazardous [7].

Municipal waste collection is normally the responsibility of some form of local government body. In the United States, MSW is usually collected by a county or, if sufficiently large, a town or city. The amount collected varies. For example, Table 4.1 indicates that the average collection needs for the state of Illinois differ substantially from its largest city, Chicago. Sometimes, national agencies designate official authorities. For example, in the United Kingdom, these bodies are known as Waste Collection Authorities (WCAs). A WCA may have its own in-house waste collection team or, in many cases, the work is contracted out to a private company.

Waste collection is often one of the most expensive operations undertaken by a local

TABLE 4.1 Total Municipal Solid Waste Allocation in the United States

Discards	Residential (%)	Commercial (%)
California	40	60
Connecticut	58	42
Illinois	51	49
Iowa	53	47
New York	54	46
Oregon	62	38
Washington	50	50
Wisconsin	41	59
Average	51	49
Range	41–62	38–59
Generation	Residential (%)	Commercial (%)
Florida	47	53
Illinois	52	48
Chicago, Illinois	39	61
Iowa	43	57
Massachusetts	41	59
New York	54	46
Average	46	54
Range	39–54	46–61
US Range	55–65	35–45

Data from U.S. Environmental Protection Agency, "MSW Residential/Commercial Percentage Allocation—Data Availability," Office of Resource Conservation and Recovery, Washington, DC, 2013. Available from: https://www.epa.gov/sites/production/files/2016-01/documents/rev_10-24-14_msw_residential_commercial_memorandum_7-30-13_508_fnl.pdf (Accessed 9 April 2018).

government. For example, in the Manila, Philippines metropolitan area, local governments spend more than \$64 million (United States) annually on the collection and disposal of MSW, which is between 5% and 24% (average 13%) of each local government's total budget [8].

Recent statistics published by the statistical office of the European Union (EU) [6] show that an average of 524 kg of municipal waste was

generated per person in 2008 across the 27 member countries of the EU, of which 40% was sent to landfill, 20% was incinerated, 23% was recycled, and 17% was composted [6]. In Florida, United States, it was reported that around 1800 kg of MSW per resident per year was collected in 2007 [3]; however, this included some construction and demolition waste which would normally be excluded from the definition of MSW. The amount of MSW generated worldwide in 2006 was estimated by Market Research.com [7] to be just over two billion tonnes.

Municipal waste collection is becoming an increasingly complicated task for WCAs to undertake, with the collection requirements of the different waste streams, e.g., dry recyclables, yard waste, glass, residual waste, etc., varying from year to year, as recycling performance improves. For example, in the United States, in 2008, some 82.9 million tons (75.2×10^6 t where t refers to metric tonne) of MSW was recycled (33% recycling rate) compared with 55.8 million tons (50.6×10^6 t) (26% recycling rate) in 1995 [9]. These changing conditions mean that waste collection round designs need to be updated regularly.

1.1 Collection Efficiency

Waste handling technologies vary by need. For example, under Germany's 2105 Waste Management Act, it is now mandatory to separate collection of all of the various waste streams comprising paper, glass, plastic, and household organic waste [7]. Various types of waste are collected separately at the collection point by using separate waste containers designated, for example, "curbside (United States) or kerbside (United Kingdom) sorting." This increases the recycling potential of the various waste types. Separate collection also enhances compliance with waste-stream specific quality standards for recycling. This is certainly not the rule for local governments, but is employed throughout the world to varying degrees. The responsibilities for collection differ, depending on where

the waste is generated along the product life cycle. The Act has also created incentives for manufacturers to minimize or eliminate waste, for example, by making products more durable. The Act is also expected to increase the effectiveness of recovery and disposal after a product's end-of-life goods (See [Chapter 2](#)).

We are again reminded of the need to address wastes systematically. Thus collection is an important, early step in proper management. Indeed, recent policies call for a systematic approach that optimizes waste alternatives within a life cycle perspective. The German law, for example, applies a multilevel hierarchy that includes waste prevention, reuse, recycling, energy recovery, with only the remainder in need of waste disposal [7].

Operating costs are minimized and maximum value is achieved when collection rounds are well designed. This includes the acquisition and proper maintenance of collection vehicles and providing optimal MSW-related infrastructure. Waste management also must hold paramount environmental considerations. For example, current government policy for England [10] states that "... better collection and treatment of waste from households and

other sources has the potential to increase England's stock of valuable resources whilst also contributing to energy policy. And achieving both of these aims helps reduce greenhouse gas emissions." Due to the large numbers of variables, objectives, and constraints, designing efficient waste collection rounds is a complex task and, consequently, optimizing round structures has received a considerable amount of attention, both from the research community and from practitioners seeking to improve their performance and reduce their costs. This chapter consolidates the research and practice to provide a summary of waste collection methods and how to models to aid design of collection rounds and estimate costs.

2 MATERIALS COLLECTED

MSW comprises a wide range of materials. The composition varies nation to nation, even for those with similar economies. As evidence, the composition of MSW generated in the United States [11] and in the United Kingdom [12] is provided in [Table 4.2](#). Some caution is needed in comparing the statistics from the

TABLE 4.2 Comparison of MSW Composition in the United States and United Kingdom

Waste Category	United States (%)	United Kingdom (%)
Paper and card	27	23
Food	16	18
Garden/yard waste	14	14
Plastics	13	10
Metals	9	4
Textiles	6	3
Wood	6	4
Glass	5	7
Other	4	17

Sources: EPA-530-F-14-001, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012, 2013*; WR0119: *Municipal Waste Composition: A Review of Municipal Waste Component Analyses—Final Report, 2009*.

two countries as the category definitions in each case were slightly different: for example, for the United Kingdom, the “other” category used here included furniture (1.3%) and WEEE (waste, electronic and electrical equipment) (2.2%), which would clearly contribute toward wood, metal, and other waste categories.

In the Guadalajara, Mexico metropolitan zone, the mean per capita daily household generation rate in 2001 was measured to be 508g. This waste consisted predominantly of putrescible waste (53%), paper (10%), and plastic (9%), with household wastes representing about 56% of MSW [13]. This would indicate that this city has a much larger amount of traditional “garbage” than the mean values for the United Kingdom and the United States, if putrescible waste can be considered food and yard waste. The mean daily generation rate of MSW in Guadalajara was over 3000t [13]. The difference between household wastes and MSW was largely due to the lower proportion of organic materials (approximately 53% vs 17%, respectively). These analyses indicate the difficulties involved in separating the various materials for subsequent disposal, recycling, or treatment. This obviously calls for a wide diversity of methods to collect the materials.

In countries with well-developed recycling policies and systems (e.g., Germany, Switzerland, Austria, Norway, Sweden, United States) households typically engage in the recycling effort by being supplied with separate bins or containers for different materials. Rather, the sorting occurs by the county after collection. The number of different containers that a household can be reasonably expected to keep is limited; A reasonable number of three containers has recently been proposed: one for dry recyclable waste (paper, cardboard, plastic bottles, etc.), one for food waste, and one for residual waste [3]. Even within these countries, however, the extent of separation varies. For example, the author’s county of residence, Chatham County, North Carolina, requires that garbage be

segregated from recyclable materials. The county, however, does not require curbside sorting.

3 COLLECTION SYSTEMS

Local jurisdictions usually apply waste collection systems that have been retrofitted from previous systems. Not so many decades ago, particularly in less urbanized areas, trash and other household wastes were burned in barrels and/or simply disposed on the owner’s residential and agricultural properties, or transported by the owner to an open dump. With the closing of these dumps and changes in practice, trash removal became more ubiquitous, even in less populated areas. Thus the major point of contact between the waste manager and the household has become the curb, that is, the nexus between the residence and the waste authority.

There are many different types of curbside collection scheme, varying widely in the types of recyclable materials targeted by individual authorities. This emanates from the different characteristics of the households within an area and the interrelationships between the various collection systems, sorting methods, and frequency of collections. Waste collection frequencies of recyclable materials in the United Kingdom and the United States can be weekly, every other week, or monthly. Increasingly common practice in the United Kingdom is alternate weekly collection (AWC), where each household has its recyclable waste and residual waste collected on alternating weeks. A common alternative scheme is to have weekly collection of residual waste and collection of recyclable waste every other week. AWC can be justified from the viewpoints of reducing collection costs and encouraging more recycling from households [14]. However, some people object to the possible health risks associated with a 2-week collection frequency for residual waste. Recyclable materials can be collected together in



FIG. 4.3 Curbside sorting of different recyclable materials. From *The Waste and Resources Action Programme*, April 12, 2018. Used with permission from WRAP.

commingled collections in one single-bodied vehicle, to be separated later, or be separated by the household for loading into separate compartments in a vehicle (Fig. 4.3) through a “curbside-sort” scheme. Recyclables can also be mixed with the residual waste and collected by the same vehicle using different colored sacks to differentiate the materials. The WCA may also offer separate collection of bulky waste (e.g., furniture, white goods), green garden waste or of hazardous waste, normally at an additional charge to the customer.

In addition to collections from individual residences, WCAs also make collections from public litter bins and from communal bins. Public litter bins located in shopping streets, parks, and so on, generally need to be emptied frequently. In the United Kingdom, such collections are normally separate from household collections, largely due to capacity. Communal bins are relatively large bins which may be used where there is a high density of residential properties like apartments or where the collection authority decides it would be too impractical

or expensive to visit properties individually. Communal bins are also commonly located at public amenity sites such as parking lots, supermarkets, or at dedicated waste drop-off sites, known in the United Kingdom as “household waste recycling centres.” Different bins can be used to collect different materials, for example, bottle banks, clothing banks, and so on.

The collection requirements for communal bins are rather different from those for household bins. The key information needed is the expected rate of fill of each bin to allow efficient collection rounds to be designed and to avoid the bin becoming full before the next collection is made, as illegal dumping of waste may be exacerbated if a communal bin becomes full. The expected fill rate may be estimated from historical data, or the bins could be equipped with sensors to detect when they are becoming full. The advantages of dynamic waste collection schedules over fixed schedules were demonstrated in Malmö, Sweden, reported by Johansson [12], where 3300 recycling containers were fitted with level sensors and wireless communication equipment, thereby giving waste collection operators access to real-time information on the status of each container.

In the United Kingdom, collections made from commercial premises are normally undertaken separately from household collections. This is mainly due to the current legislation which excludes commercial waste from being counted toward MSW recycling targets. WCAs are not obliged to offer trade waste collection services and, indeed, many in the United Kingdom do not, and the waste is collected by private waste contractors. In principle, where the waste generated by businesses is similar in composition to household waste (e.g., paper, cardboard) then there may be operational benefits available through combining the collections together. However, there may be scheduling difficulties associated with the larger businesses requiring more frequent collections (e.g., daily) whereas household collections are typically on a weekly basis.

Pay-as-you-throw (PAYT)—recycling by households can be encouraged by variable charging for residual waste collection according to the weight (or volume) collected. There are about 7000 such schemes in operation in the United States with increases in recycling between 25% and 69% in the first year being reported [15]. An alternative scheme is to provide households with some form of incentive to recycle. Miami, Florida, for example, issued coupons in March 2009 for use at local retail stores according to the amount of waste they recycled. This was reported to increase recycling in areas where there was little before, which adds credence to the use of monetary incentives and free market actions to enhance mandatory programs.

The importance of citizen awareness and changes in societal attitudes should not be underestimated. For example, waste collection burden is reduced in ways other than by public mandate. We are reminded that waste minimization and sorting are not the exclusive province of governments. Indeed, material exchange programs, such as those implemented by charitable organizations, also play an important role in waste reduction and recycling. Items that may have been collected as trash only a few years ago are now seen for their potential other reuses or repurposing and donated to thrift shops. The easing of waste collection demand also shows up at less organized and difficult-to-track material exchanges, for example, flea markets and yard sales [16].

3.1 Waste Collection Vehicles

The vehicles used for waste collection range from relatively small handcarts, in developing countries, to state-of-the-art refuse collection vehicles (RCVs) equipped with hydraulic bin-lifting gear. The simplest form of bin-lifting equipment requires the bin to be mounted onto a hoist by an operator, typically at the rear of the vehicle (Fig. 4.4). Vehicles that load bins from the front or from the side are also available, with the former often used to empty containers from commercial premises.



FIG. 4.4 Rear-loading refuse collection vehicle. From <https://partners.wrap.org.uk/assets/7471/>. Used with permission from WRAP.

Multicompartment vehicles are sometimes used to collect different materials at the same time, for example, recyclable waste alongside residual waste. While collecting different materials at the same time may bring about operational efficiencies—for example, a cost reduction of 15% was reported for a case study in Brescia, Italy [13]—their use may not be appropriate in some situations, particularly where the different materials collected have to be delivered to different locations that are far apart, or where the volumes to be collected are variable. The latter situation can lead to one vehicle compartment reaching capacity quicker than the other, requiring the vehicle to empty mid-round which may not be optimal.

The capacities for carrying waste vary widely for vehicles. Vehicle costs are proportional to capacity, so this is clearly a major factor affecting collection costs. Typical carrying capacity needs in the United Kingdom, for example, range between 8 and 12 t to collect household residual waste. Given the lower mean density of recyclable waste, the same vehicle capacity for recyclable waste is about 25% less than what is required for residual waste, even after compaction. For optimal collection efficiency, the vehicle used

should be as large as possible, to reduce the number of trips made to a waste disposal site, recycling facility, or transfer station; however, there are practical limitations on the size of vehicle that may be used both in urban and rural areas. For example, road widths, weight, and other access restrictions may require smaller vehicles. Where transfer stations are deployed for intermediary storage and waste consolidation, the onward movement of waste from the transfer station to the end disposal site tends to be undertaken by large road vehicles or, in some cases, the transfer station may have intermodal facilities to enable onward movement of waste by rail, for example, train, tram, or by water, for example, canal barge, short sea shipping [17].

4 MODELING PROBLEMS AND METHODS

Waste collection is a multifaceted problem that can be considered at different levels, from the high level, strategic, policy, or planning viewpoints, such as where to locate facilities, how to define collection boundaries, which

materials to collect, and how often to collect them, to more low level, tactical or operational decisions, such as when to visit the waste disposal site on a vehicle round or which route to take to avoid traffic congestion. The main issues require specific consideration in the following sections.

4.1 Siting Collection-Related Facilities

The locations of waste disposal sites, transfer stations, recycling centers, and other facilities associated with waste disposal, in relation to each other and in relation to the households and businesses being served, will clearly have a significant impact on waste collection costs. Ideally, these costs should be estimated and included whenever locations for new facilities are being decided; however, this is easier said than done, as the combined facility location and vehicle routing problem is very difficult to solve, and heuristic methods tend to be based on iteration between the two separate problems [18–20].

Decisions on new disposal sites tend to be based on environmental, land use, and land availability considerations rather than on transport costs. Economic considerations play a large role since, in the Europe, North America, and elsewhere, transport costs generally are much lower than acquisition costs for real estate. Social attitudes are also important drivers in these decisions. Waste handling facilities are often perceived as threats to neighborhood quality and land values (See [Discussion Box 4.1](#)).

The location of the vehicle depot also has a significant impact on waste collection costs. Vehicle depot location theory has historically been based on placing the depot at the center of gravity of the population being served [28]. However, this cannot be assumed for the waste collection requirements associated with visiting a waste disposal site or a recycling center before returning to the vehicle depot. Indeed, a study

by the authors of the first edition chapter [29] found that minimizing waste collection vehicle costs requires that the vehicle depot be located as close as possible to the main waste disposal site, or transfer station, being used. An estimated vehicle mileage savings of 13.5% was reported when vehicles were moved from their existing depots to a hypothetical depot based at the waste disposal site for three adjoining WCAs in the county of Hampshire in England.

4.2 Districting and Privatization

“Districting” refers to the partitioning of a larger region into smaller districts. The statistics and models can be more targeted and focused to address the specific waste needs. Thus each district has unique and separate waste collection challenges. Optimization is simplified and computations and modeling needs are clearer than those of the larger region. Even with these more specific parameters, districting introduces only a small degree of suboptimality [30]. Districting theory is based on producing compact districts with evenly balanced workloads [31]. A savings of 14% in deadhead mileage through was reported in Antwerp, Belgium resulting from improvements to the existing district definitions [32].

Local authorities may also use districting as part of their evaluation of privatized waste collection service and costs. Most waste collection in the Europe [33] and the United States has been privatized [34] and is common throughout the world [35]. The decision to privatize has depended on the waste manager and planner’s recommendation to elected and appointed officials. These recommendations have depended on research, but usually rested largely on the unique knowledge and “intuition” of the waste manager. Some factors are quantifiable, for example, organizational values, level of service and rate control, impacts to waste reduction and recycling goals, and impacts to public

DISCUSSION BOX 4.1 NIMBY [21]

The acronym “NIMBY,” not in my backyard, came into prominence and joined the global vernacular in the late 1970s. This was a time where people were becoming acutely aware of the possible dangers of modern society. They were taking to the streets (and the beaches and rivers and swamps...) to protest site recommendations for nuclear power plants, wastewater treatment facilities, solid and hazardous waste landfills, chemical manufacturing plants, and a myriad of other projects that they perceived to be a health threat to their neighborhoods and homes.

An environmental response is often precipitated first by a complaint. But to complain, one must have a “voice.” If a certain group of people has had little or no voice in the past, they are likely to feel and be disenfranchised. Although there have been recent examples to the contrary, African-American communities have had little success in voicing concerns about environmentally unacceptable conditions in their neighborhoods. Hispanic-Americans may have even less voice in environmental matters since their perception of government, the final arbiter in many environmental disagreements, is one of skepticism and outright fear of reprisal in the form of being deported. So, many of the most affected communities are not likely to complain.

Land use is always a part of an environmental assessment. However, justice issues are not necessarily part of these assessments. If you search most environmental impact assessment handbooks prior to the late 1990s, you would have a difficult time finding anything related to fairness issues in terms of housing and development. They are usually concerned about open space, wetland and farmland preservation, housing density, ratios of single versus multiple family residences, owner occupied housing versus rental housing, building height, signage and other restrictions, designated land for public facilities like landfills and treatment works, and

institutional land uses for religious, health care, police, and fire protection.

When land uses change (usually, to become more urbanized), the environmental impacts may be direct or indirect. Examples of direct land use effects include eminent domain, which allows land to be taken with just compensation for the public good. Easements are another direct form of land use impacts, such as a 100m right-of-way for a highway project that converts any existing land use, for example, farming, housing, or commercial enterprises, to transportation-related uses. Land use change may also happen indirectly, such as from secondary effects of a project. That is, the project itself does not cause the problem but it allows conditions to change in time and space. These changes lead to future stresses on communities.

Secondary or indirect impacts may be obvious for activities and land uses other than environmental actions, for example, a new road may exacerbate sprawl by providing previously unavailable access to suburban or exurban development. However, secondary impacts may also result from actions taken to improve the environment. For example, if the community land use thoughtfully considers areas that presently on in the future will need clean water. As such, they may build new drinking water supplies and a wastewater treatment plant. They will also likely connect and expand new lines to these facilities. This will then create accessibility which spawns suburban growth [22]. This can also result from expansion of MSW collection serves. Thus environmental problems can result from improvements to affordable housing and waste handling. This is an example of risk trade-offs that may arise from decisions driven and constrained by a complex array, that is, decision space, consisting of economic, political, societal, esthetic, and technological factors [23].

Continued

DISCUSSION BOX 4.1 NIMBY (cont'd)

Sometimes, the imposition of NIMBY is intentional. No matter the subdivision, most building lots were once woodland, farmland, or other open spaces. Often, had it not been for some expenditure of public funds and the use of public powers like eminent domain, the development would not have occurred. Also, if services like waste collection were provided by local jurisdictions, homeowners in these subdivisions would have to expend substantial funds to address waste and other environmental and esthetic challenges.

Ironically, public assets and resources are used to subsidize wealthy neighborhoods with services, like waste collection. In the meantime, these services, combined with environmental and zoning regulations may work against affordable housing. Even worse, environmental protection may be used as a rationale for elitist and exclusionary decisions. In the name of environmental protection, certain classes of people are restricted from living in certain areas. This problem first appeared in the United States in the 1960s and 1970s in a search for ways to preserve open spaces and green areas. One measure was the minimum lot size. The idea was that rather than having the public sector, secure land through easements or outright purchases (i.e., fee simple) to preserve open spaces, developers could either set aside open areas or require rather large lots to have their subdivisions approved. Thus green areas would exist without the requisite costs, including operation and maintenance, entailed by public parks and recreational areas. However, this often translated into higher costs for residences. The local rules for large lots that result in less affordable housing are known as “exclusionary zoning” [24, 25]. In this case, one value, for example, open space and green areas, conflicts with another, that is, affordable housing. In these instances, it has been argued that ostensibly preserving open

spaces was simply a tool for excluding lower SES people or even people of minority races [25].

Housing advocacy groups, for example, Habitat for Humanity, propose development of affordable houses. These developments may be in or near existing neighborhoods, including those with average home values much higher than the proposed development. The Habitat model offers a combination of financial incentives, personal and familial pride of ownership, community participation, and affordable housing. Thus potential homeowners invest in their own homes through “sweat equity” and receive voluntary support. It is not unusual for opposition to such a plan. Nearby residents have argued that the new homes be incompatible with some aspect of the existing neighborhood, for example, lot size, esthetics, or structural factors. Even if true, the result of such thinking is, in the end, exclusionary. People are very passionate and protective about their neighborhoods, well beyond concern about property values. These NIMBY arguments are common in public service and other engineering endeavors. The waste manager must be ever mindful of the need to balance science and social needs to site unpopular facilities like landfills and treatment plants.

Waste managers must be sensitive to the fact that most of us want to protect the quality of neighborhoods but, at the same time, waste managers need to work with engineers and land use planners to ensure that their noble objective, that is, environmentally sound waste management, are not used as a rationale for unjust means. Environmental laws and policies, like zoning ordinances and subdivision regulations, should not be used to keep lower SES groups out of privileged neighborhoods. For example, when asked to propose a design for a waste transfer facility, the waste manager must be fair and courageous when selecting the site, notwithstanding pressure

DISCUSSION BOX 4.1 NIMBY (cont'd)

from well-funded and politically powerful NIMBY opponents to the best plan.

This falls under the aegis of “environmental justice” [26]. Historically, certain groups have borne disproportionate exposure to pollution. Some of this occurred unintentionally, because of migrations near pollution sources. Highly polluted industrial sites near US cities were home to working class, predominantly white workers and their families for several decades in the first half of the 20th Century. In fact, in the United States, even well-paid plant managers lived near their factories. Much of this was dictated by available transportation. Plant owners often lived well away from the plant, since they had the means and the flexibility to visit as needed. Before air and water pollution controls became prevalent, people living near steel mills, coke ovens, chemical processing facilities, and power plants were exposed to visible plumes of pollutants. As workers could move away to less polluted neighborhoods, lower income people moved in. Many of these low-income families were not employed at the polluting plant. Over time, these undesirable

neighborhoods were populated largely by African-Americans. In some cases, the neighborhoods continued to change from predominantly African-American populations to recently arrived immigrants, especially of Hispanic descent [27].

Incidental injustice has been associated with higher than average pollutant exposures, but intentional injustice also continues. Polluting and otherwise unpopular facilities, including waste treatment, storage, and disposal facilities, continue to be sited in areas inhabited by lower SES groups at a much higher rate than in higher SES neighborhoods [27]. This can be due to the subtle and often unstated rationale that few if any complaints are lodged against these siting decisions. If people do not complain sufficiently the siting action continues unabated. Thus a complaint-based system is a middle or even upper-class NIMBY tool. Compared to the higher SES groups, lower SES neighborhoods have historically had little or no “voice” in these matters. The waste manager must ensure that the best options are selected, not simply those with the fewest complaints.

employment. Others are difficult to quantify in models, community pride and public perceptions, and ability to respond to technological, regulatory, and socioeconomic changes [36].

Privatization is a rather encompassing term, including contracting, concession, franchise, and open competition [35]. In contracting, the governmental body funds a private entity to deliver MSW collection services, often with other services, for example, street sweeping, recycling, transfer operations, disposal site maintenance, and vehicle maintenance. The difference between an outright contract and a concession is that, in the latter, the government

funds the private entity to establish a program that uses a government-owned system, for example, refuse. Like contracting, the concession is for a finite amount of time, although in some jurisdictions, the private firm may hold the ownership and operations indefinitely. A franchise can be a district-level “monopoly” awarded to a private firm, after competition. To attain the franchise, the firm must provide assurances of quality and scope, for example, a performance bond and license fees to pay for the government’s monitoring of the franchised firm. Open competition delegates the performance to the household and establishments in

the district. The firms will have had to meet similar requirements to those of franchises [35].

The waste manager can apply models to inform decision-makers or residents on how to delineate districting factors when dividing a large area into several districts. For example, a compactness factor can steer districts away from land parcels, although it cannot ensure road network integrity given that collection activities occur along road networks for the most part. Waste collection districting models are being enhanced, for example, by counting the number of points crossing the boundary of a candidate district. In Taiwan [34], for example, this approach was used to address the road network integrity needed for a routing plan. Along with spatial compactness and road network integrity factors, such a model can be used to compare proximity among districts. The increased proximity can lower the cost difference among districts, so that it increases competition in the bidding process for MSW collection services.

4.3 Defining Collection Points

The number of individual households in a waste collection authority area is usually large, so modelers generally group households together to form a reduced number of collection points [14]. Various approaches for aggregating collection are applied in different models, including:

1. street level, particularly where an arc routing model is used with arcs corresponding with streets [37];
2. postcode level [29];
3. block level [38]; and
4. macro-point level [39], defined as a cluster of collection points close to each other and sharing similar properties in terms of waste collection requirements.

The volume of collected waste from each collection point can be estimated based on the numbers of premises at each collection point and on

the total volume of waste that is normally collected on a round. These estimates may also have to take the sociodemographic characteristics of the properties or areas into account, if there are wide differences between areas, for example, in the type of housing (e.g., flats, size of property) or type of household (e.g., size of family, wealth) [40, 41].

4.4 Vehicle Routing and Scheduling

Vehicle routing and scheduling theory is vast, covering many different types of problem and situation, so it is recommended that the waste manager become familiar with the state of the science [39, 42–52]. While some algorithms proposed in the literature may be applied directly to the waste collection problem, certain characteristics of waste collection may limit their use or require modifications. One such characteristic is the typical requirement for the collection vehicle to make more than one visit to a waste disposal site during the round. Other factors that may have to be taken into consideration include [1]:

- Avoiding main roads at peak traffic periods
- Avoiding schools at opening and closing times
- Road network restrictions pertaining to vehicle weight, height, turning, or other access restrictions
- Whether access is from the front or rear of the property
- Collecting from each side of a street separately where it would not be safe for the crew to walk back and forth across the street
- Avoiding awkward turning movements—for example, for countries that drive on the right-hand side of the road, some left turns may be difficult due to oncoming traffic.
- One-way streets—it is likely to be most efficient if any one-way streets are entered at their furthest upstream points.

- Steep hills—from fuel consumption and emissions perspectives, steep hills are best climbed near the start of the round when the vehicle is not carrying much load. Also, where feasible, waste on a steep hill is best collected on both sides of the street while the vehicle is moving downhill to facilitate safety, ease, and speed of collection and to reduce wear and tear on the vehicle [26].
- Time constraints include the waste disposal site opening hours and the staff working hours. Collections from commercial premises may also have to be made within stated time windows.

Such modeling considerations are common in environmental modeling. For example, terrain complexity must be considered in air pollution dispersion modeling [53], driver behavior in air quality “mobile source,” that is, vehicle emissions, modeling, and user idiosyncrasies in predictive modeling of potential exposure to chemicals in consumer products [54–58].

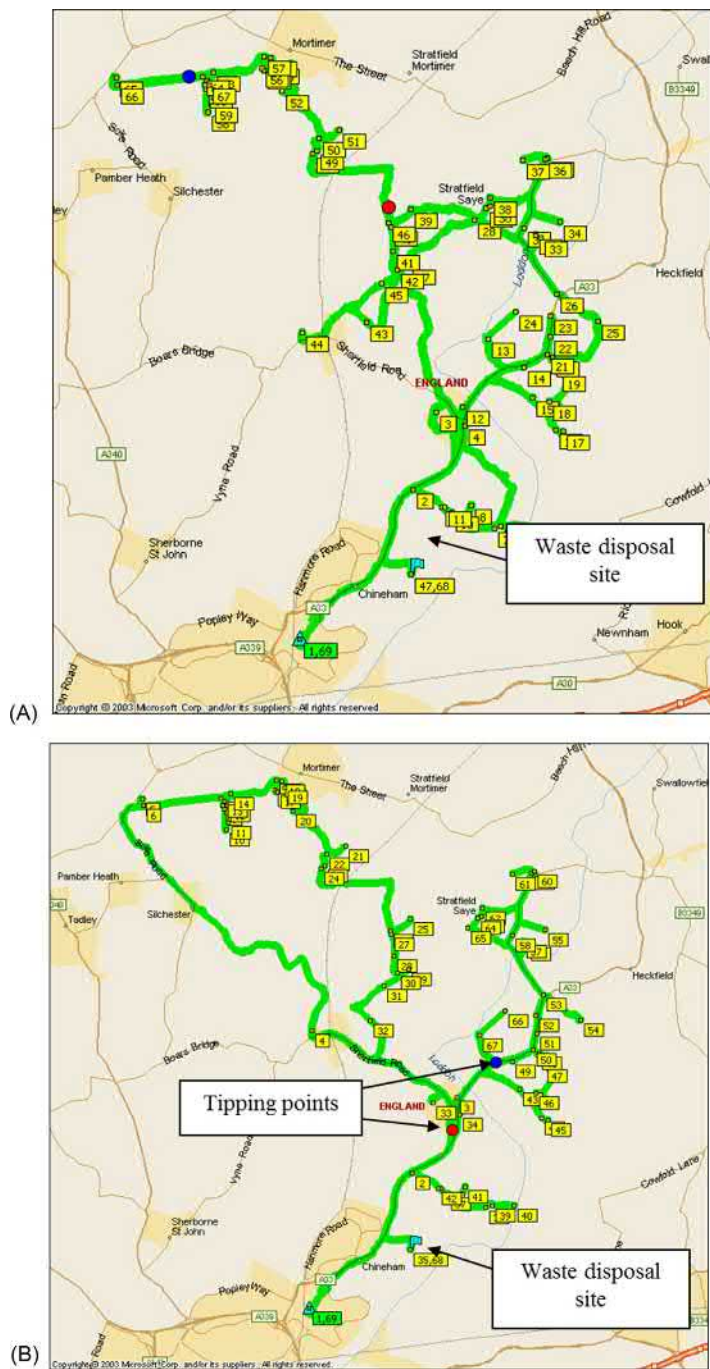
Optimizing waste collection normally involves a fleet of collection vehicles to undertake specified collections at the minimum possible cost. In this situation, most of the operating costs relate to time taken and distance traveled. Related objectives include rounds that are compact and well balanced, so that the work is distributed fairly and/or proportionately among the collection rounds. The balanced use of the waste disposal points was also sometimes desired, for example, Porto Alegre Brazil’s balanced assignments of collection trips in which impoverished cooperatives unload at recycling facilities [59].

With few exceptions, any waste collection problem is difficult to solve. Even if constraints such as those listed before are not considered, the problem of using capacity-constrained vehicles cannot be solved optimally for more than about 100 collection points; however, the best models are able to obtain good solutions for large numbers of collection points [42]. This insolvable problem calls for many alternative

heuristic methods, such as geographic information systems (GIS), branch-and-bound, tabu search, insertion, removal and clustering methods, fuzzy logic, and genetic algorithms. Examples of heuristic algorithms that have been developed and applied to waste collection problems include those by Akhtar et al. [60], Gómez and Pacheco [61], Desai et al. [62], Abdelli et al. [63], Kuo and Zulvia [64], De Rosa et al. [37], Viotti et al. [65], and Bautista and Pereira [66]. These and other researchers provide specific rationales for their approaches, so the methods chosen to optimize waste collection depend on local conditions. There are also many commercially available vehicle routing and scheduling software packages available, employing such techniques, that can suggest new round designs and vehicle routes which may improve significantly upon existing ones, particularly where the current rounds have not been updated for some time. These packages may include parameters that affect how the algorithms operate, for example, controlling how collection points are grouped to form clusters. In some cases, there may be a trade-off between run time and accuracy and some trial and error experimentation with the settings may be needed.

Vehicle routing and scheduling models can be particularly useful in selecting optimal “tipping points,” that is, the points at which a trip to the waste disposal site (tip) is made. Intuitively, these will tend to be made when the vehicle is almost full; however, this may not be the best strategy. For example, tipping when the vehicle is closest to the waste disposal site but not full may be a better approach, depending on the spare capacity. Vehicle routing and scheduling models can be useful for suggesting round designs that may not be obvious or intuitive to the waste collection manager. For example, in a study undertaken by the authors for the UK Department for Transport [32], the collection time for one round was reduced from 8.5 to 7 h by improving the tipping points and reconfiguring the route (See Fig. 4.5).

FIG. 4.5 (A) Original modeled route with poorly placed tipping points; (B) Redesigned route with tipping points closer to the waste disposal site. From F. McLeod, T. Cherrett, *Waste collection*, in: *Waste*, Elsevier, 2011, pp. 61–73.



Like any model, vehicle routing and scheduling models are simplifications of reality. For waste collection, numerous factors interact in complex ways. These interactions cannot be completely enumerated or properly parameterized, so the model will not completely reflect real-world outcomes. Some of the areas of waste collection modeling inaccuracies and uncertainties can be attributed to weak or erroneous default values, data scarcity, and insufficient data quality, such as:

1. Definition of the collection points (e.g., street, postcode), which contributes to model coarseness.
2. Specification of the available road network, including any vehicle weight, height, turning movement, access, and other restrictions.
3. Travel speed assumptions.
4. Assumptions about volume of waste to be collected.
5. Assumptions regarding the time needed to collect the waste.

Often, model accuracy and representativeness suffers from a lack of available detailed data and the expense of obtaining such data. The errors and uncertainty are propagated and can compound (See Fig. 4.6). This means that routes and schedules produced by models generally must be checked and modified by an experienced manager with reliable local knowledge before implementation.

5 DATA REQUIREMENTS FOR MODELING

The main data requirements for modeling waste collection relate to the volume and/or weight of waste to be collected, the time needed for loading and unloading waste, and the travel time between collection points.

5.1 Waste Volume and Weight

Waste volume and weight data are normally collected by WCAs for reporting and performance management purposes. These data show how the amount of waste collected varies over time. The amount of waste to be collected at any given time is clearly an important consideration in planning vehicle round structures and routes. The traditional approach to working with variable data has been to estimate average figures and treat the problem as a static, deterministic one [1]. This may not be satisfactory, however, if the routes and schedules produced are infeasible on days when the amount of waste to be collected is above average. For this reason, some slack normally must be built into the design to be able to cope in such situations. Another approach is to try to model the variability explicitly [20, 38, 67–70]. A dynamic routing and scheduling approach using GPS and weight sensors [71] is another option; however, this is not generally adopted given the complexities and sophistication of the approach.

5.2 Loading and Unloading Times

The time needed to load the waste into the vehicle at each collection point is crucial to waste collection dynamics. The time is a function of various factors, commonly including the properties at the collection point; the number of bins, bags, or other units of waste set out for collection; the volume of waste and walking distances between the vehicle and the waste containers, for example, bins and bags. Although this information is not normally directly measured it can be estimated from round times, by accounting for travel times to and from the waste disposal sites, and from the numbers of properties, bins, and so on. For example, loading times of residual waste from domestic properties in Hampshire, United Kingdom were estimated as

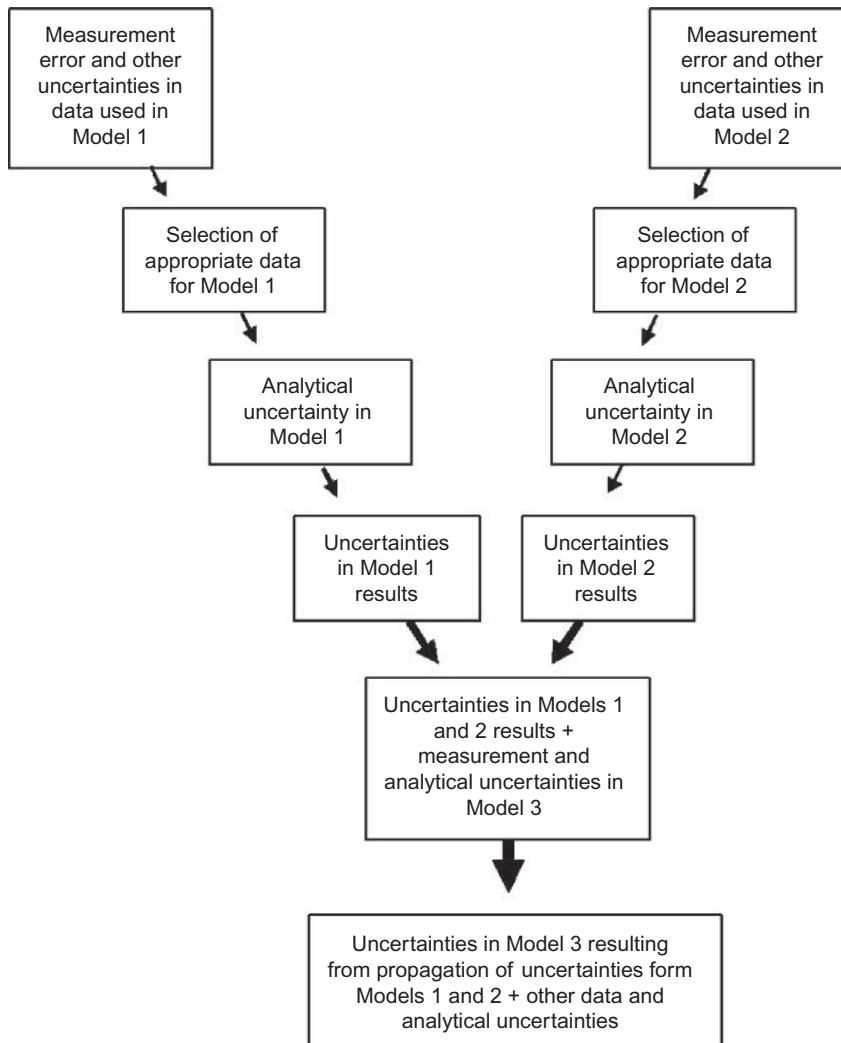


FIG. 4.6 Sources and propagation of error and uncertainty in a model. From D. Vallero, *Environmental Biotechnology: A Biosystems Approach*. Elsevier Science, 2015.

1.2 s kg^{-1} , which equated to about 14s per bin [29]. Other factors will change these estimates. For instance, loading times, in seconds, of yard waste (described as grass, leaves and brush) in Oklahoma, United States were estimated by:

$$(\text{SOR}) \times (\text{NOR}) [9.23 + (11.6 \times \text{AU})] \quad (4.1)$$

where SOR=set out fraction (the proportion of households putting waste out); NOR=number

of residences at the collection point; and AU=average number of units (bin, bag, bundle) at a residence.

The unloading time at a waste disposal site can either be modeled as a fixed average time. For example, a survey by 628 vehicle trips at a landfill site near Southampton, United Kingdom gave an average turnaround time of 11 min [72]. Variability may also be explicitly modeled by

taking any waiting factors into account, for example, the variability due to the number of vehicles queuing to use the facilities [73].

5.3 Travel Times

Travel times between collection points, and from the collection area to and from the waste disposal site, can be estimated by observing typical vehicle running speeds. Vehicle speed depends on the size and engine power of the vehicle, the road network, for example, considering road widths, traffic lights, and the amount of traffic on the road. Normally, vehicle rounds are designed to avoid main roads during peak traffic periods, both to avoid delays to the collection vehicles and to avoid disruption and delays to drivers given the relatively slower moving waste collection vehicles. The avoidance assumes substantially reduced travel speeds on certain roads at certain times of day, which renders them unattractive for use. An even more sophisticated approach is to incorporate real-time traffic data into the waste collection model [74]. Computational, real-time models are becoming available to optimize collection times and to find feasible solutions that may result in financial savings in comparison to a practical lower bound that is based on flexible routes [75].

modelers can be overly optimistic in our estimates and predictions. Assuming a “spherical chicken” makes the math easier in designing the perfect chicken coop, but the waste manager’s best approach is to consider the waste collection “beaks and claws” for the real-world waste collection challenges of the specific locality.

6.1 Hampshire, United Kingdom

Commercially available vehicle routing and scheduling software was used to assess benefits associated with joint working between three neighboring WCAs in Hampshire, United Kingdom (Basingstoke and Deane, Hart and Rushmoor), comprising around 130,000 households. This joint working effectively removed the existing collection boundaries between the authorities and allowed vehicles to be moved to a neighbor’s depot. A total of 25 rounds (=25 vehicle days) were selected as being most suitable for joint working, as they lay closest to the existing boundaries between the authorities. Redesigning these rounds resulted in: one fewer vehicle days’ work; a time savings of 1.4% (approximately 6 min per vehicle day); a vehicle mileage savings of 5.9% (approximately 3.3 km per vehicle day); and an annual distance savings of around 4300 km, which was estimated to be equivalent to an annual cost savings of around £35,000 and a carbon savings of around 2.1 t [76].

6 EXAMPLE STUDIES

Case studies from around the world can help to illustrate of the benefits that may be possible by waste collection routing and scheduling models. Comparisons between studies are difficult given the operating conditions tend to be unique to each and since the results are very much dependent on the quality of the original routes that were used in the base cases. It also seems likely that in many cases, reported results may present an idealized scenario, as various practical restrictions or modeling limitations may not have been fully considered. We

6.2 Taipei City, Taiwan

Joint working between Taipei City (12 districts in the center of the region) and Taipei County (29 districts surrounding the city), Taiwan, with a total population of around 6 million and served by a waste collection fleet of just over 1000 vehicles, was estimated to achieve annual savings of around US \$4 million over the existing system where all 41 districts operate independently. This estimate was based on a model devised by Chang et al. [77], which

employed specific goal constraints in an integer programming model.

6.3 Porto Alegre, Brazil

Societal factors can greatly influence the efficacy of waste collection. As previously mentioned, Porto Alegre has provided interesting insights into waste collection in an area with limited finances [59]. Thus collection cannot follow the typical waste collection approach adopted by many local authorities. Among the collection objectives is the need to balance the rounds to make equal use, as reasonably as possible, of recycling centers run by cooperatives whose members are poor and who gain financially through use of their facilities. Their heuristic approach, which incorporated an auction algorithm and a dynamic penalty method, was shown to reduce the number of truck days per week required from 103 to 77, with the total distance traveled in a week reducing from 2418 to 1760 km (27% savings), when compared with the existing rounds. The stated objective of balancing the use of the recycling centers was also achieved.

6.4 Finland

Nuortio et al. [78] presented waste collection vehicle routing and scheduling results, based on a “guided variable neighborhood thresholding metaheuristic,” for three real-life waste collection problems in eastern Finland. Vehicle distance savings were 4% in one case and 44% in the other two, although the latter savings were partly due to some clearly inefficient operating practices in the “before” case.

6.5 Life Cycle Analysis

Since waste collection presents a complex challenge with environmental importance, it should make use of emerging environmental systems tools. GIS and complex environmental models were mentioned previously, but another

important tool is the life cycle analysis (LCA) (See Chapter 2). Laurent et al. [79] recently found that waste collection has lagged behind many other environmental planning initiatives insofar as their use of LCAs. They performed a critical review of 222 published LCA studies of solid waste management systems. They found that published studies have primarily been concentrated in Europe with little application in developing countries. They and others [80] encourage waste managers to use LCA to capture the local specific conditions in the modeling of environmental impacts and benefits of a waste management, which will improve identifying critical problems and improvement options that can be adapted to these local conditions and needs.

7 CONCLUSIONS

From engineering and management perspectives, waste collection is the crucial nexus between waste generation and waste disposition. A review of the literature indicates that other aspects of MSW management and research receive greater attention, for example, recycling. However, these initiatives depend on effective and efficient waste collection.

Waste collection is a multifaceted and highly complex problem with no easy solutions. Common solutions are also difficult to identify due to the huge diversity of operating conditions throughout the world. It is very much in the interests of WCAs worldwide to devise efficient working methods to keep their operating costs as low as possible while providing a good level of service to households, trade customers, and other interested parties. This chapter has introduced the waste materials that are collected, the collection systems that are typically used, and the types of vehicles and other equipment used. It has also described vehicle routing and scheduling, in terms of its capabilities, limitations, data requirements and has provided some

case study examples from around the world to give an indication of the range of waste collection problems and of what benefits may be achievable by improving waste collection vehicle routing and scheduling methods.

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Waste and Biogeochemical Cycling

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1 INTRODUCTION

The earth is a dynamic system of systems in which matter and energy cycle into and out of myriad compartments in the environment. The amount, the chemical form, and the location determine whether a chemical substance is essential or detrimental. Nitrogen (N), for example, is an indispensable nutrient for plants. However, plants can only use certain bioavailable forms in soil. Under many conditions, such as excessive concentrations, transformations by biota into toxic chemical forms, or moving into drinking water supplies, this same N can become air, water, and soil pollutants.

Both matter and energy cycle through the environment, so an understanding of wastes requires consideration of the physical mechanisms by which substances and energy move and change. These mechanisms can be combined with the inherent properties of a chemical to estimate the extent to which a chemical will be more or less likely to move and where it may move in the environment. The physical and chemical mechanisms and properties will also determine the fate of a chemical, especially how it may become more or less toxic and more or less mobile.

The biogeochemical cycle is a systems concept. That is, it is a way to address wastes and

other pollution by considering how matter and energy move through trophic states within biological organizations and how the abiotic, non-living components of a system interact with the biotic, living components. It is a means of keeping track of the mass and energy balances, both thermodynamically and fluid dynamically [1].

This chapter specifically addresses the cycles of water, carbon, and the environmental nutrients, especially N and sulfur (S). The cycles of other substances are also important to waste management. The metal cycles are addressed in [Chapter 6](#) and energy is discussed in this chapter as part of the biogeochemical cycles, for example, light in photosynthesis and the role of heat in solubility and volatilization. The heat cycle is also discussed in [Chapters 20 and 32](#).

2 THE HYDROLOGIC CYCLE

The features of the water molecule (see [Fig. 5.1](#)) have helped to shape the earth's surface, as it interacts with another global sphere, the lithosphere. Water's interaction is done by through physical and chemical processes (see [Fig. 5.2](#)).

Physically, for example, the molecular configuration engenders its substantial expansion by volume as it freezes or sublimates (i.e., change of state from gas to solid); the latter initiates frost heaving, one of the mechanisms needed to break down rock formations. The resulting unconsolidated materials eventually become soil [2].

Chemically, this molecular configuration is responsible for water's ability to dissolve many chemical compounds, including acids that react with compounds in solid rock, for example, within fissures and crack, changing the geomorphology of the terrain. The alignment of a water molecule's oxygen and two hydrogen atoms gives a slightly negative charge at the oxygen end and a slightly positive charge at the hydrogen ends. Given that "like dissolves like," polar

substances have an affinity to become dissolved in water, and nonpolar substances resist being dissolved in water. The hydrogen atoms form an angle of 105° with the oxygen atom. The asymmetry of the water molecule leads to a dipole moment in the symmetry plane toward the more positive hydrogen atoms.

Biologically, these and countless other physical chemical processes make the original rock material suitable for microbial and root growth. Lichen and other simple plant systems further break down the rock and its unconsolidated materials, setting the stage for larger plant growth. As a result, the terrain hardly resembles the original rock formation.

The hydrosphere is the discontinuous stratum around the earth that holds its water in many forms, including groundwater beneath the surface, surface water, water in soil and biota, and moisture and vapor in the atmosphere. The fluid properties of air and water combine in the hydrosphere, not only making weather, but to move and transform all types of chemical compounds, including pollutants. The atmosphere holds 0.0055% of the earth's total amount of water (0.04% of freshwater) compared to the oceans which hold 96.5% of the earth's water (see [Table 5.1](#)). However, the atmosphere accounts for much of water's activity on earth, from weather systems to nutrient cycling to pollutant transformation (e.g., hydrolysis), as well as pollutant transport and deposition. [3]

2.1 The Hydrosphere

All waste management activities take place in the hydrosphere, whether it is exchange of pollutants between ground and surface waters and the atmosphere, the storage of pollutants in soil water or the release, and the biota's uptake of pollutants after their release (see [Fig. 5.3](#)).

Waste is impacted by and affects the water cycle. For example, water allows microbial populations to grow and break down wastes

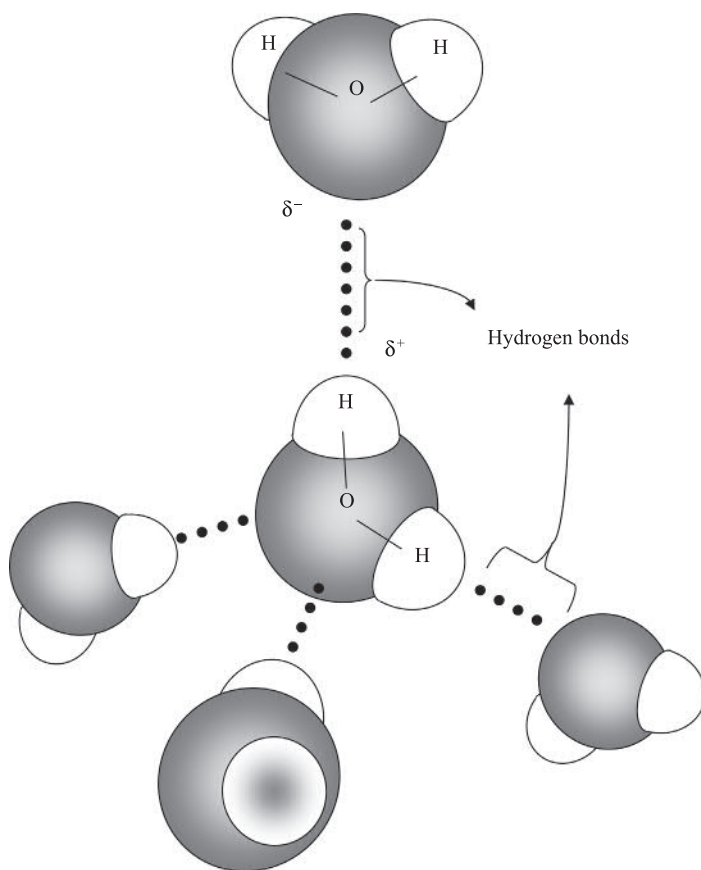


FIG. 5.1 Configuration of the water molecule, showing the electronegativity (δ) at each end. The hydrogen atoms form an angle of 105° with the oxygen atom. Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999.

in landfills and other facilities. Pollutants that are released from these facilities can be transformed by hydrolysis and other chemical reactions in water, whether in receiving water bodies, soil, roots, or droplets suspended in the atmosphere. These processes help to degrade the pollutants, but can also make some pollutants even more toxic. These aerosols can be removed from the atmosphere by several processes. Both homogeneous and heterogeneous reactions occur in waste systems. If the reaction only occurs in the gas phase, the reaction is homogeneous. If the reaction involves an interface with a surface of an aerosol or within a liquid droplet, it is heterogeneous. Certain chemical species of sulfur (S) and N have

sufficient aqueous solubility to be dissolved by the droplet. These liquid-phase compounds are already acidic (e.g., including concentrations of H_2SO_4 , H_2NO_3 , and H_2CO_3) before washout. Thus the water droplet plays a key role in both dry and wet deposition of pollutants that lead to acidic conditions in soils and surface waters (see Fig. 5.4).

The total amount of water in the hydrosphere is constant, but its location and quality vary in time and space. Waste managers and engineers must account for possible changes in weather, climate, and other hydrological conditions with time. It is reasonable and prudent to expect changes over the life of a waste design. Mean global and local temperature increases due to

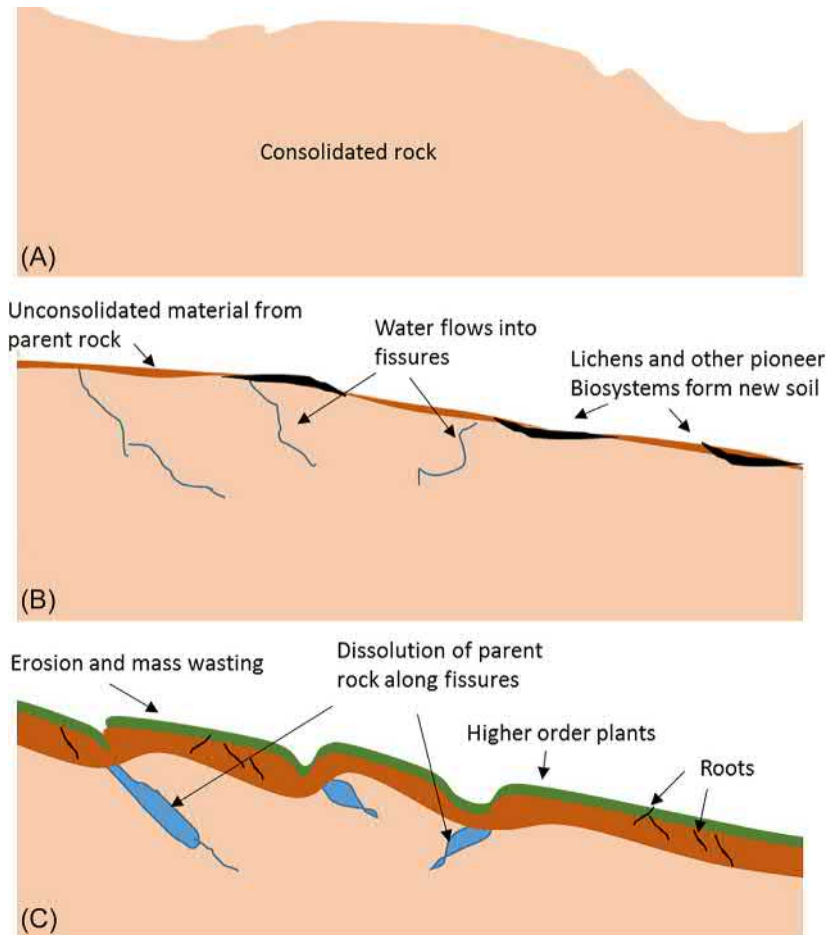


FIG. 5.2 Side view example of some of the many physical, chemical, and biological mechanisms that change terrain. (A) Initial rock formation. (B) Erosion and weather form pockets of unconsolidated material as matrices for early soils. Water flows into fissures and widens them by chemical reactions, for example, carbonic acid in limestone. (C) Early microbial and plant root systems continue to deepen the soil horizons and to smooth the terrain.

increased atmospheric concentrations of global greenhouse should be factored into designs and facility siting decisions [8, 9]. For example, certain facilities should be hardened or simply not be built in areas potentially affected by rising water levels on coasts, as well as on other large water bodies, for example, the Great Lakes in North America (see Fig. 5.4). In addition, the relationships between water supplies and waste facilities can be affected by changes in

hydrological and hydraulic conditions, for example, the salt water wedge encroaching inward (see Fig. 5.5). The density difference between fresh and saltwater can be a slowly unfolding disaster for the health of people living in coastal communities and for marine and estuarine ecosystems. Salt water contains a significantly greater mass of ions than does freshwater (see Table 5.2). The denser saline water can wedge beneath freshwaters and

TABLE 5.1 Estimation of Water Volume in the Hydrosphere

Water Source	Water volume ($\times 1000 \text{ km}^3$)	Percent of Earth's Freshwater	Percent of Total Water
Oceans, seas, and bays	1.338×10^6	—	96.5
Ice caps, glaciers, and permanent snow	24,064	68.6	1.74
Groundwater	23,400	—	1.7
Fresh	10,530	30.1	0.76
Saline	12,870	—	0.93
Ground ice and permafrost	300	0.86	0.022
Lakes	176.4	—	0.013
Fresh	91	0.26	0.007
Saline	85.4	—	0.007
Soil moisture	16.5	0.05	0.001
Atmosphere	12.9	0.04	0.001
Swamp water	11.5	0.03	0.0008
Rivers	2.1	0.006	0.0002
Biological water	1.1	0.003	0.0001

Sources: P.H. Gleick, *Water in Crisis: A Guide to the World's Fresh Water Resources*, 1993, U.S. Geological Survey (2016), *The World's Water*. Available: <https://water.usgs.gov/edu/earthwherewater.html>.

pollute surface waters and groundwater. This phenomenon, known as saltwater intrusion, can significantly alter an ecosystem's structure and function, and threaten freshwater organisms. It can also pose a huge challenge to coastal communities who depend on aquifers for their water supply. The freshwater Everglades, for example, recharge the Biscayne aquifer, a natural underground layer that collects water. The Biscayne aquifer is the primary water supply to the Florida Keys.

The effect in sensitive coastal habitats like those in South Florida would be exacerbated by the rising sea level, which could submerge low-lying areas of the Everglades (see Fig. 5.6), increasing the salinity in portions of the aquifer. The rising seawater could force salty waters upstream into coastal areas, thus threatening

surface water supplies. Furthermore, any waste disposal practices in these sensitive areas would be sources of additional contaminants. Similar problems could also occur in Northeastern U.S. aquifers that are recharged by fresh portions of streams that are vulnerable to increased salinity during severe droughts. [8] Indeed, similar groundwater-surface water-seawater interactions could be affected across the globe. Unfortunately, planning of waste management facilities often lacks the methods and tools to make decisions to optimize siting alternatives, although geographic information systems (GIS) and other tools are increasingly assisting in these efforts [10].

Salinity of water is a relative term. The values in Table 5.2 are at best averages and target concentrations. Actually, salinity is the total

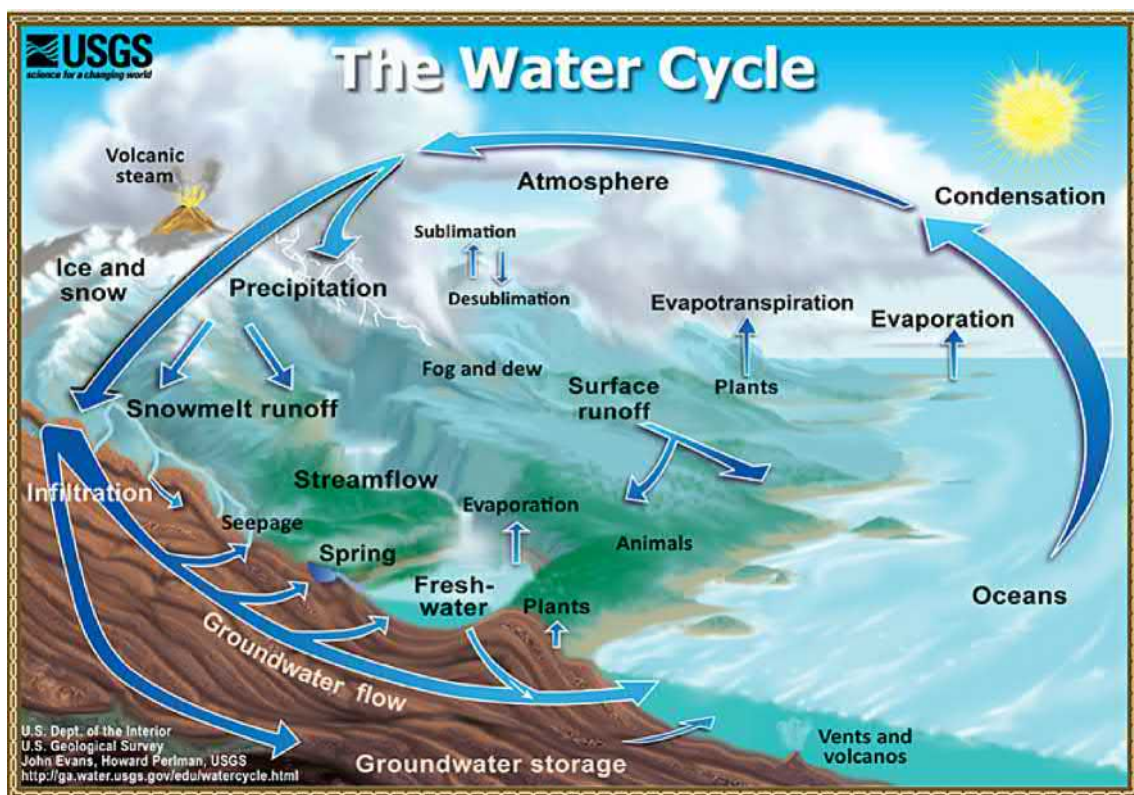


FIG. 5.3 The hydrological (water) cycle. U.S. Geological Survey (2013). Summary of the Water Cycle. Source: U.S. Geological Survey, Summary of the Water Cycle, 2016. Available: <https://water.usgs.gov/edu/watercyclesummary.html>.

concentration of dissolved solids (TDS). Indeed, in the United States, the drinking water standard for TDS is a “secondary” or nuisance standard, which is 500 mg L^{-1} . Note that the classifications using two dominant ions, Na^+ and Cl^- differ by three orders of magnitude between “fresh” and “saline” waters. Consider the hypothetical example in Fig. 5.7 of these ionic strengths (indicated by TDS) before and after saltwater intrusion. Although the water near the water supply is not “saltwater,” nor does it currently violate the secondary drinking water standard, the ionic concentrations are cause for concern and serve as a warning that the trend is likely to be toward even higher salinity.

The foregoing discussion illustrates how an indirect effect (atmospheric warming from emissions of greenhouse gases) can lead to hydrospheric impacts (warming and sea level rise) and freshwater contamination. Adding another potential stressor, for example, a land-fill, further complicates this. The interconnectedness of the atmosphere, hydrosphere, and biosphere is complex and extensive (see Fig. 5.8). A small change in one small part of the spheres can lead to unanticipated outcomes. Thus hydrologic cycling specifically and biogeochemical cycling generally are sensitive to initial conditions and, as such, must be treated as chaotic systems.

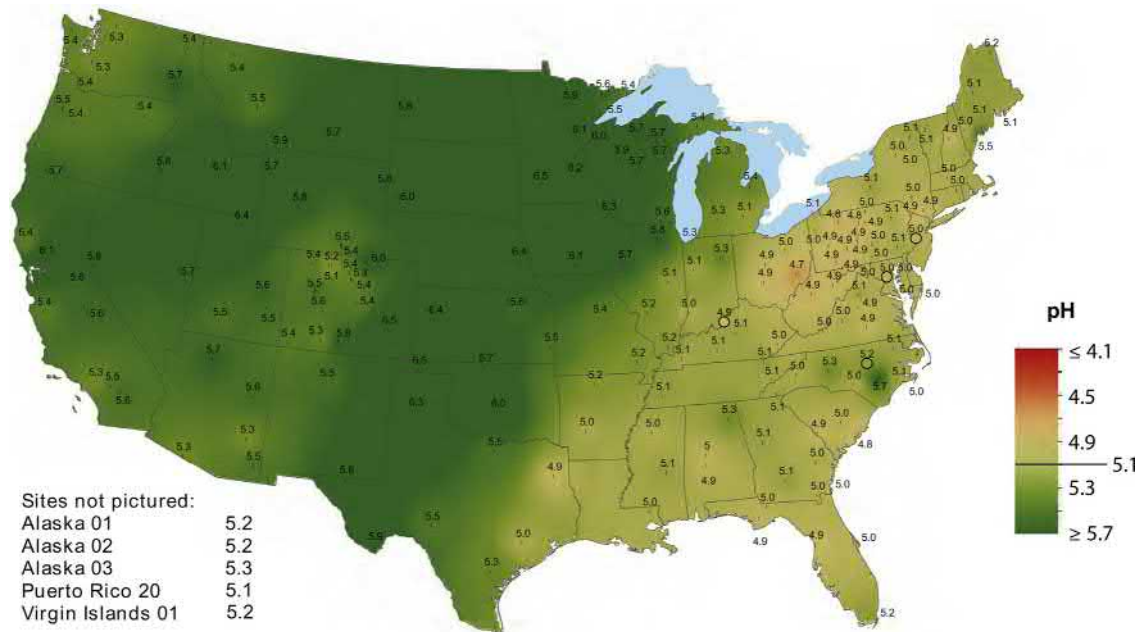


FIG. 5.4 Precipitation-weighted mean pH in wet deposition for the year 2012. Source: Illinois State Water Survey, University of Illinois at Urbana-Champaign, NADP Data Report 2013-01, National Atmospheric Deposition Program: 2012 Annual Summary, 2013.

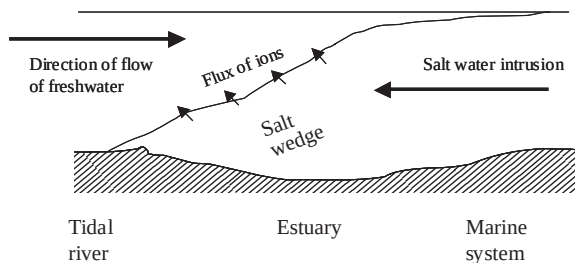


FIG. 5.5 Saltwater intrusion into a freshwater system. This denser saltwater submerges under the lighter freshwater system. The same phenomenon can occur in coastal aquifers.

3 SCALE AND COMPLEXITY OF MATTER AND ENERGY CYCLES

Matter and energy cycling takes place at all levels, each of which is important to waste management. Energy cycling can begin with the release of heated plumes from incinerators, but also from composting facilities and landfills. Exchanges between the hydrosphere, atmosphere, and lithosphere, for example, soil and sediment, create sinks and sources of energy.

Heat reservoirs in terrestrial and aquatic systems receive added heat, which when released can alter habitats (e.g., changes to freeze-thaw cycles, seasonal variations, and selectivity of certain soil bacteria genera).

Mass and energy cycling commonly occurs within the hydrologic cycle. The law of conservation of mass and the first law of thermodynamics (both refer to closed systems) dictates that these cycles be both mass and energy balanced. Some of these water-energy relationships

TABLE 5.2 Important General Ionic Composition Classifications of Freshwaters and Marine Waters

Composition	River Water (M)	Salt Water (M)
pH	6–8	8
Ca ²⁺	4×10^{-5}	1×10^{-2}
Cl [−]	2×10^{-4}	6×10^{-1}
HCO ₃ [−]	1×10^{-4}	2×10^{-3}
K ⁺	6×10^{-5}	1×10^{-2}
Mg ²⁺	2×10^{-4}	5×10^{-2}
Na ⁺	4×10^{-4}	5×10^{-1}
SO ₄ ^{2−}	1×10^{-4}	3×10^{-2}

Here, *M* refers to molarity (moles per liter solution).

Sources: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015; P.M. Gschwend, *Environmental Organic Chemistry*, John Wiley & Sons, 2016; J.P. Kim, K.A. Hunter, M.R. Reid, factors influencing the inorganic speciation of trace metal cations in fresh waters, *Marine Freshw. Res.* 50(4) (1999) 367–372; R.P.

Schwarzenbach, P.M. Gschwend, D.M. Imboden, *Organic acids and bases: acidity constant and partitioning behavior*, *Environ. Org. Chem.* (1993) 245–274.

are obvious and direct, for example, the thermal inversions that lead to urban air pollution are the result of differences in heat energy in water vapor at various layers in the troposphere. Some of the water-energy relationships are incremental and indirect, such as the transfer of energy between trophic states in an ecosystem, which relies in part on energy and water exchanges among biotic tissue and abiotic substrates (e.g., aqueous-phase phosphorous (P) compounds that transfer energy during photosynthesis).

Water-energy cycling is also important in anthropogenic systems and is part of a design of pollution control equipment selection and application. For example, at the facility scale, water and energy are often addressed together, such as the management of water and energy at a factory or power plant. Managing water is a simultaneous process with managing energy. Indeed, mismanagement of water systems at the facility level can involve trade-offs between types of pollution. Again, the first law requires, for example, that allowing heated water to be

released in any amount, even the permitted level, would increase the overall temperature of the receiving waters.

The heat from boilers and other industry-scale operations is going to be exchanged. This is a consideration of not only air pollution and water pollution control decisions, but also of waste management decisions. Facility design determines in large part where the energy goes (see Fig. 5.9). In fact, a pollution control and heat control design can directly affect dissolved oxygen (DO) content of the receiving water temperature since temperature is directly proportional to DO content. The DO is a limiting factor of the type of fish communities that can be supported by a water body (see Tables 5.3 and 5.4). The resulting net increase in heat may directly stress the biotic integrity of a surface water ecosystem, for example, fish species vary in their ability to tolerate higher temperatures, meaning that the less tolerant, higher value fish will be inordinately threatened.

The increased temperature can also increase the aqueous solubility of substances toxic to organisms. For example, greater concentrations of mercury and other toxic metals will occur with elevated temperatures. The lower DO concentrations will lead to a reduced environment where the metals and compounds will form sulfides and other compounds that can be toxic to the aquatic life. Thus the change in temperature decreases the concentrations of DO and increases metal concentrations. The synergistic impact of the hypoxic water and reduced metal compounds becomes a cascade of harm to the stream's ecosystems.

The biota also play a role in a heat-initiated effect and combined abiotic and biotic responses occur. Notably, the growth and metabolism of the bacteria results in even more rapidly decreasing DO levels. Algae both consume DO for metabolism and produce DO by photosynthesis. The increase in temperature increases their aqueous solubility and the decrease in DO is accompanied by redox changes, for

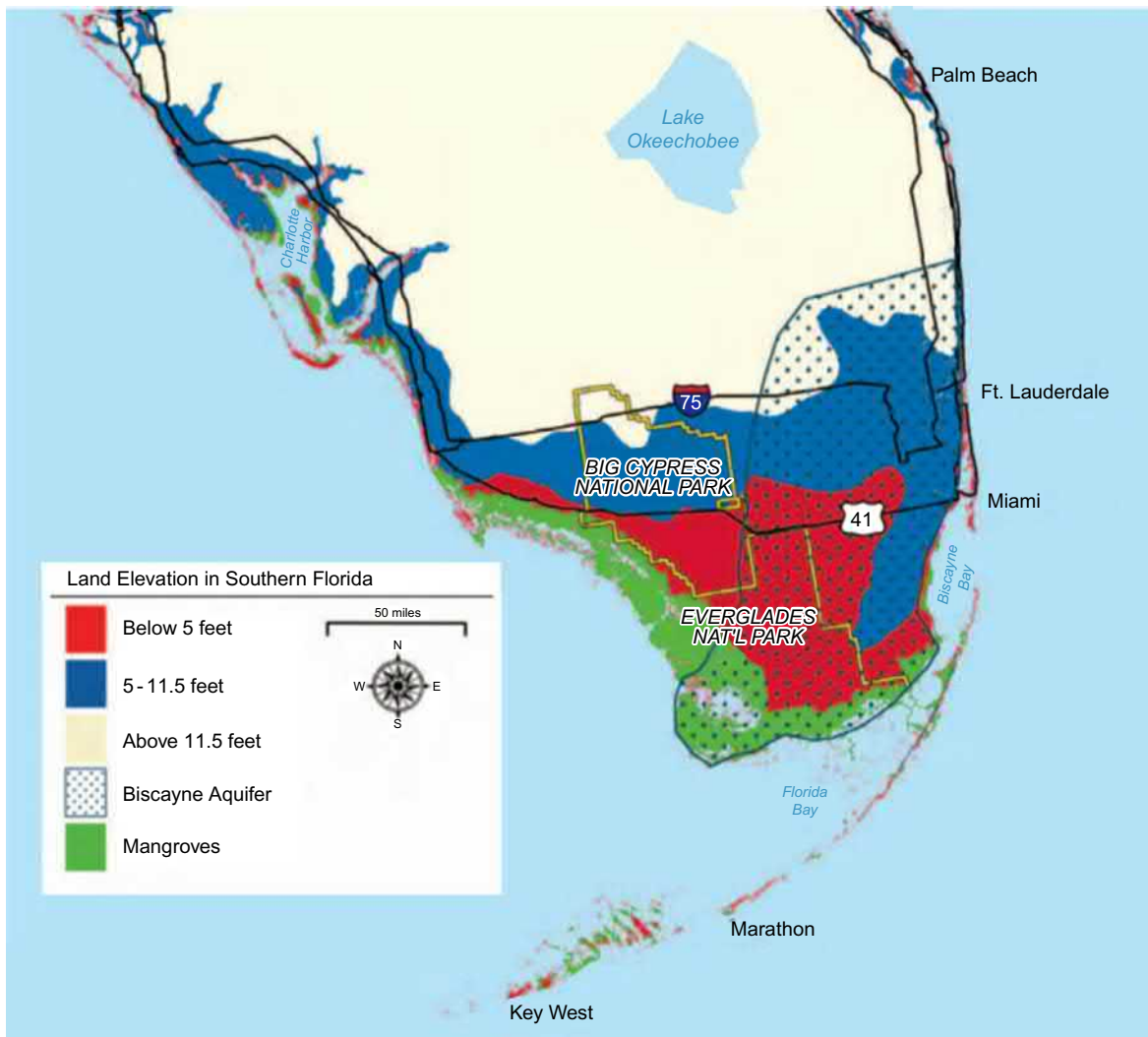
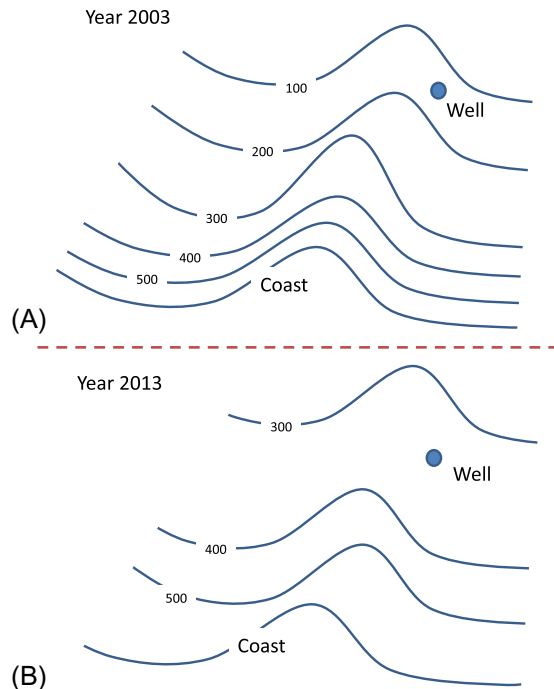


FIG. 5.6 Elevation and aquifer locations in southern Florida. Although a small part of the aquifer is beneath salty mangrove area, most of it is recharged by the freshwater Everglades, rendering the area vulnerable to saltwater intrusion and increased salinity of both surface and groundwater sources of drinking water. Modified from U.S. Environmental Protection Agency, *Saving Florida's Vanishing Shores*, 2002. Available: http://www.epa.gov/climatechange/Downloads/impacts-adaptation/saving_FL.pdf.

example, formation of reduced metal species, such as metal sulfides. This is also being mediated by the bacteria, some of which will begin reducing the metals as the oxygen levels drop (reduced conditions in the water and

sediment). However, the opposite is true in the more oxidized regions, that is, the metals are forming oxides. The increase in the metal compounds combined with the reduced DO, combined with the increased temperatures can act

FIG. 5.7 Hypothetical isopleths of total dissolved solids (mgL^{-1}) concentrations in groundwater (e.g., 30m depth). The increases over the decade indicate saltwater intrusion and potential contamination at the drinking water well site. Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015.



synergistically to make the conditions toxic for higher animals, for example, a fish kill.

The initiating abiotic effect (i.e., increased temperature) results in an increased microbial population. The associated decline in DO, however, is a net decline between photosynthetic and nonphotosynthetic microbes. The growth and metabolism of the bacteria result in decreasing the DO levels, but the growth of the algae both consume DO for metabolism and produce DO by photosynthesis.

Meanwhile a combined abiotic and biotic response occurs with the metals. The increase in temperature increases their aqueous solubility and the decrease in DO is accompanied by redox changes, for example, formation of reduced metal species, such as metal sulfides. These changes can increase the exposure of human populations to toxic substances. The increase in temperature in Fig. 5.9, for example,

leads to increased solubility of metals in water. With rising temperature, the suspended or settled solids will begin to release metals at a faster rate. The process is also being mediated by the bacteria, some of which will begin reducing the metals as the oxygen levels drop (reduced conditions in the water and sediment). However, the opposite is true in the more oxidized regions, where the metals are forming oxides. The increase in the metal compounds combined with the reduced DO, in the presence of increased temperatures can act synergistically to make the conditions toxic for higher animals, for example, a fish kill. [18] Predicting the likelihood of ecosystem change and adverse events like fish kills can be quite complicated, with many factors that either mitigate or exacerbate the outcome (see Fig. 5.10). The increase in metal concentrations in water not only increases the potential exposure to and risks from all metals,

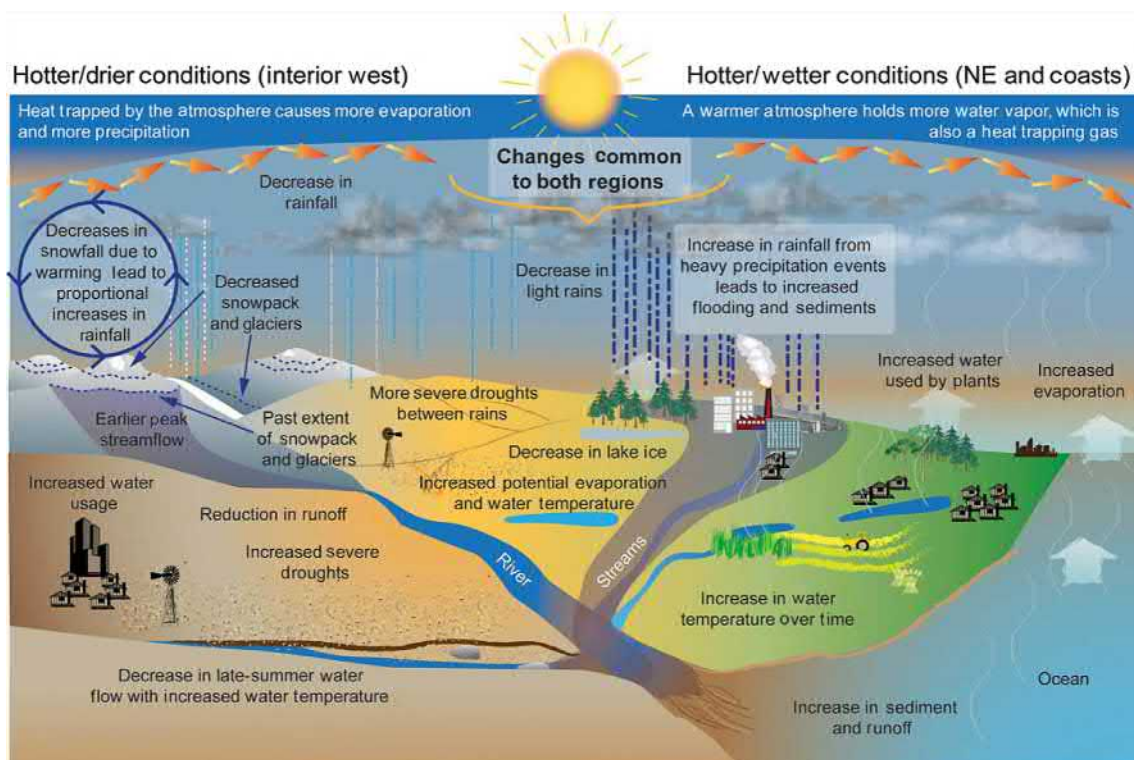


FIG. 5.8 Potential impacts of climate change of the hydrologic cycle. Source: U.S. Environmental Protection Agency, *Climate Impacts on Water Resources*, 2016. Available from: <https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-water-resources.html>. Based on information from: T.R. Karl, J. Melillo, T. Peterson, *Global Climate Change Impacts in the United States*, *Global Climate Change Impacts in the United States*, 2009.

but also the transformation of metals into different chemical species. If these new compounds have higher bioavailability, then exposure, dose, and body burden of the metals will also likely increase (e.g., methyl mercury in fish ingested by humans).

Almost any waste management facility will release substances, including contaminants, into the environment. After release, many processes and exchanges occur among and within the environmental compartments (see Fig. 5.11), as well as those at the interface between the organism and the environment. The equilibrium and speciation of elements in the atmosphere, hydrosphere, and biosphere determines their importance to waste management. Thus waste

managers need a modicum of knowledge about the biogeochemical cycling, especially for carbon and nutrients.

4 CARBON EQUILIBRIUM AND CYCLING

Many of carbon-based molecules exist in equilibrium with one another. For example, Fig. 5.12 demonstrates the equilibrium among carbonates, bicarbonates, organic compounds, carbonic acid, and carbon dioxide. On a global scale, the mean pH of uncontaminated rain is about 5.6, owing to its dissolution of carbon dioxide, CO_2 . As the water droplets fall through

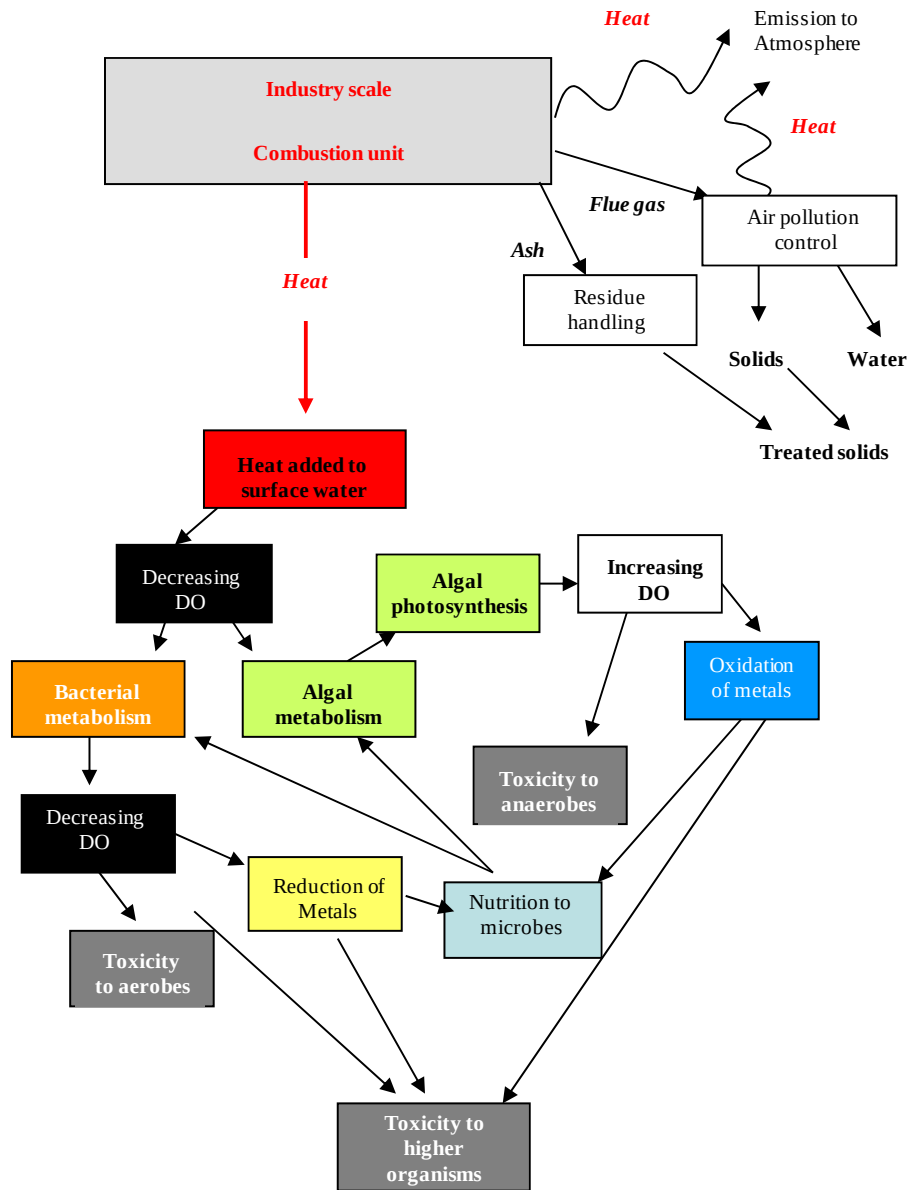


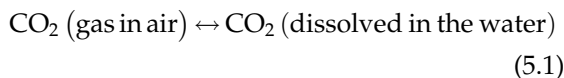
FIG. 5.9 Physical, chemical, and biological linkages in waste management. In this example, both energy and matter must be considered in a waste management decision, for example, to incinerate industrial or municipal wastes. The control of matter leaving the combustion unit must be optimized with the transfer of energy. The added heat results in an abiotic response (i.e., decreased dissolved oxygen (DO) concentrations in the water), which leads to biotic processes that either increase or decrease DO and increase the toxic responses (e.g., low DO and increase in metal bioavailability). Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999.

TABLE 5.3 Relationship Between Water Temperature and Maximum Dissolved Oxygen (DO) Concentration in Water (at 1 atm)

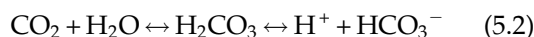
Temperature (°C)	Dissolved Oxygen (mg L ⁻¹)	Temperature (°C)	Dissolved Oxygen (mg L ⁻¹)
0	14.60	23	8.56
1	14.19	24	8.40
2	13.81	25	8.24
3	13.44	26	8.09
4	13.09	27	7.95
5	12.75	28	7.81
6	12.43	29	7.67
7	12.12	30	7.54
8	11.83	31	7.41
9	11.55	32	7.28
10	11.27	33	7.16
11	11.01	34	7.16
12	10.76	35	6.93
13	10.52	36	6.82
14	10.29	37	6.71
15	10.07	38	6.61
16	9.85	39	6.51
17	9.65	40	6.41
18	9.45	41	6.41
19	9.26	42	6.22
20	9.07	43	6.13
21	8.90	44	6.04
22	8.72	45	5.95

Sources: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Academic Press, 2010; E. Dohner, A. Markowitz, M. Barbour, J. Simpson, J. Byrne, G. Dates, 5.2. Monitoring and assessing water quality, in: *Volunteer Stream Monitoring: A Methods Manual*, 1997.

the air, the CO₂ in the atmosphere becomes dissolved in the water, setting up an equilibrium condition:



The CO₂ in the water reacts to produce hydrogen ions, as



Assuming the mean partial pressure CO₂ in the air to be 3.0×10^{-4} atm, the pH of water in equilibrium can be calculated. Such chemistry is always temperature dependent. Henry's law states that the concentration of a dissolved gas is directly proportional to the partial pressure of that gas above the solution:

$$p_a = K_H [c] \quad (5.4)$$

where K_H = Henry's law constant, p_a = partial pressure of the gas, and $[c]$ = molar concentration of the gas.

Or,

$$p_a = K_H C_W \quad (5.5)$$

where C_W is the concentration of gas in water.

Here, Henry's Law is a function of a substance's solubility in water and its vapor pressure and expresses the proportionality between the concentration of a dissolved contaminant and its partial pressure in the open atmosphere at equilibrium. That is, the Henry's Law constant is an example of an equilibrium constant, which is the ratio of concentrations when chemical equilibrium is reached in a reversible reaction and at a time when the rate of the forward reaction is the same as the rate of the reverse reaction.

TABLE 5.4 Normal Temperature Tolerances of Aquatic Organisms

Organism	Taxonomy	Range in Temperature Tolerance (°C)	Minimum Dissolved Oxygen (mgL ⁻¹)
Trout	<i>Salma</i> , <i>Oncorhynchus</i> , and <i>Salvelinus</i> spp.	5–20	6.5
Smallmouth bass	<i>Micropterus dolomieu</i>	5–28	6.5
Caddisfly larvae	<i>Brachycentrus</i> spp.	10–25	4.0
Mayfly larvae	<i>Ephemerella invaria</i>	10–25	4.0
Stonefly larvae	<i>Pteronarcys</i> spp.	10–25	4.0
Catfish	Order Siluriformes	20–25	2.5
Carp	<i>Cyprinus</i> spp.	10–25	2.0
Water boatmen	<i>Notonecta</i> spp.	10–25	2.0
Mosquito larvae	Family Culicidae	10–25	1.0

Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Academic Press, 2010. Data acquired from: V. Corporation, Computer 19: Dissolved Oxygen in Water, 2018. Available from: http://www2.vernier.com/sample_labs/BWV-19-COMP-dissolved_oxygen.pdf.

VAPOR PRESSURE AND WASTE MANAGEMENT

Vapor pressure is commonly used to categorize pollutants. Volatile organic compounds (VOCs) readily move to the headspace of a container or to the atmosphere. Generally, these compounds have vapor pressures greater than 10–2 kPa [21]. Others have proposed alternate ways to classify VOCs, such as evaporation rates over time, for example, what remains after six months [22]. Thus waste facilities handling VOCs must take care that they are not moving to the atmosphere and exposing nearby communities. The semivolatile organic compounds (SVOCs) comprise some of the most toxic, bioaccumulating, and persistent environmental contaminants, and have vapor pressures between 10–5 and 10–2 kPa. These values correspond to classifications that are based

upon observations of the compounds' behaviors during air sampling [21]. A particularly important aspect of SVOCs is that they may be transported from soil in the gas phase or as aerosols [23]. Thus if SVOCs are present in the wastes stream or storage, they must be monitored as both vapor and particulate matter.

Often VOCs are released to the atmosphere during thermal treatment of solid wastes, as are SVOCs. In addition, ash and residues contain products of incomplete combustion, such as polycyclic aromatic hydrocarbons, dioxins, furans, and hexachlorobenzene, as well as numerous pesticides, phenolics, solvents, and pharmaceuticals, which fall under the SVOC chemical classification. Proper management of wastes laden with these chemicals requires an understanding of the factors that lead to the release, movement, and degradation of these compounds.

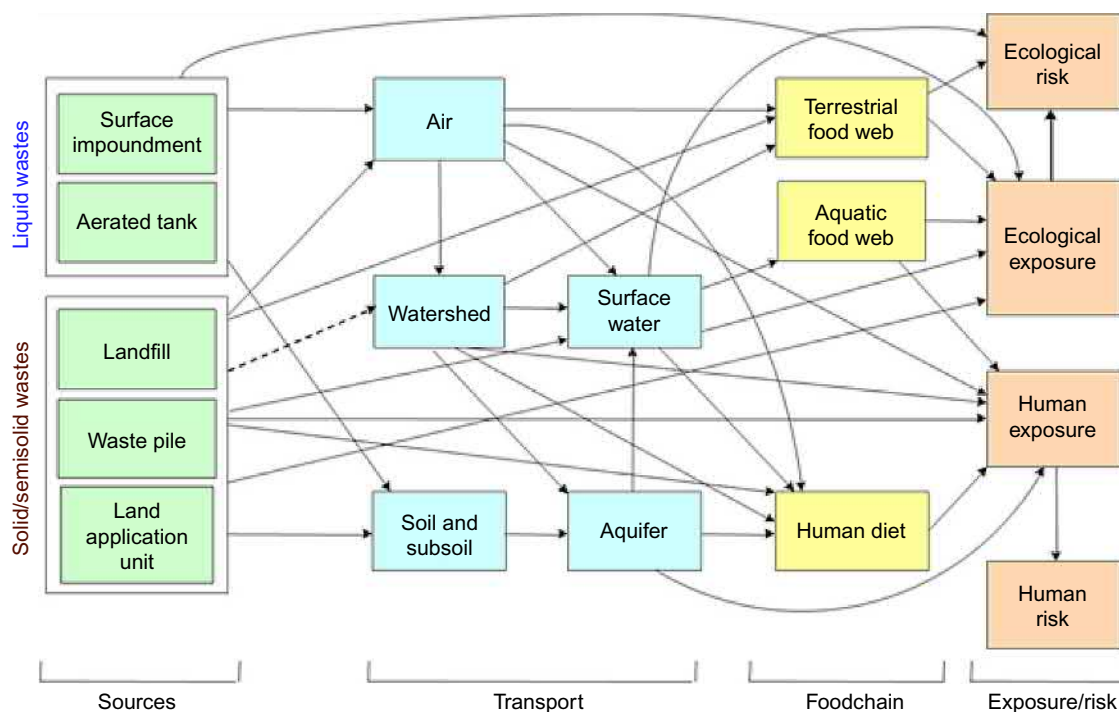
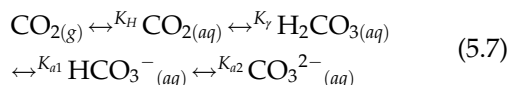


FIG. 5.10 Environmental transport pathways can be affected by net heat gain. Compounds (nutrients, contaminants), microbes and energy (e.g., heat) follow the path through the environment indicated by arrows. The residence time within any of the boxes is affected by abiotic conditions, including temperature. Sources: D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*, Academic Press, 2017; Adapted from D.A. Vallero, K.H. Reckhow, A.D. Gronewold, *Application of multimedia models for human and ecological exposure analysis*, in: *International Conference on Environmental Epidemiology and Exposure*, International Society of Exposure Analysis, Durham, NC, 2007.

The CO_2 concentration of the water droplet at equilibrium with air is obtained from the partial pressure of Henry's law constant:

$$p_{\text{CO}_2} = K_H [\text{CO}_2]_{\text{aq}} \quad (5.6)$$

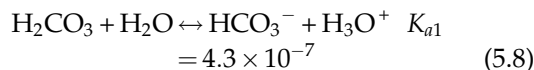
The change from carbon dioxide in the atmosphere to carbonate ions in water droplets follows a sequence of equilibrium reactions:



The processes that release carbonates increase the buffering capacity of natural soils against the effects of acidic water ($\text{pH} < 5$). The ionic

strength of the receiving soil or surface waters determines the actual change in pH. For example, the carbonate-rich soils like those in central North America are able to withstand even elevated acid deposition compared to the thin soil areas, such as those in the Canadian Shield, the New York Finger Lakes region, and much of Scandinavia.

The concentration of CO_2 is constant, since the CO_2 in solution is in equilibrium with the air that has a constant partial pressure of CO_2 . The two reactions and ionization constants for carbonic acid are as follows:



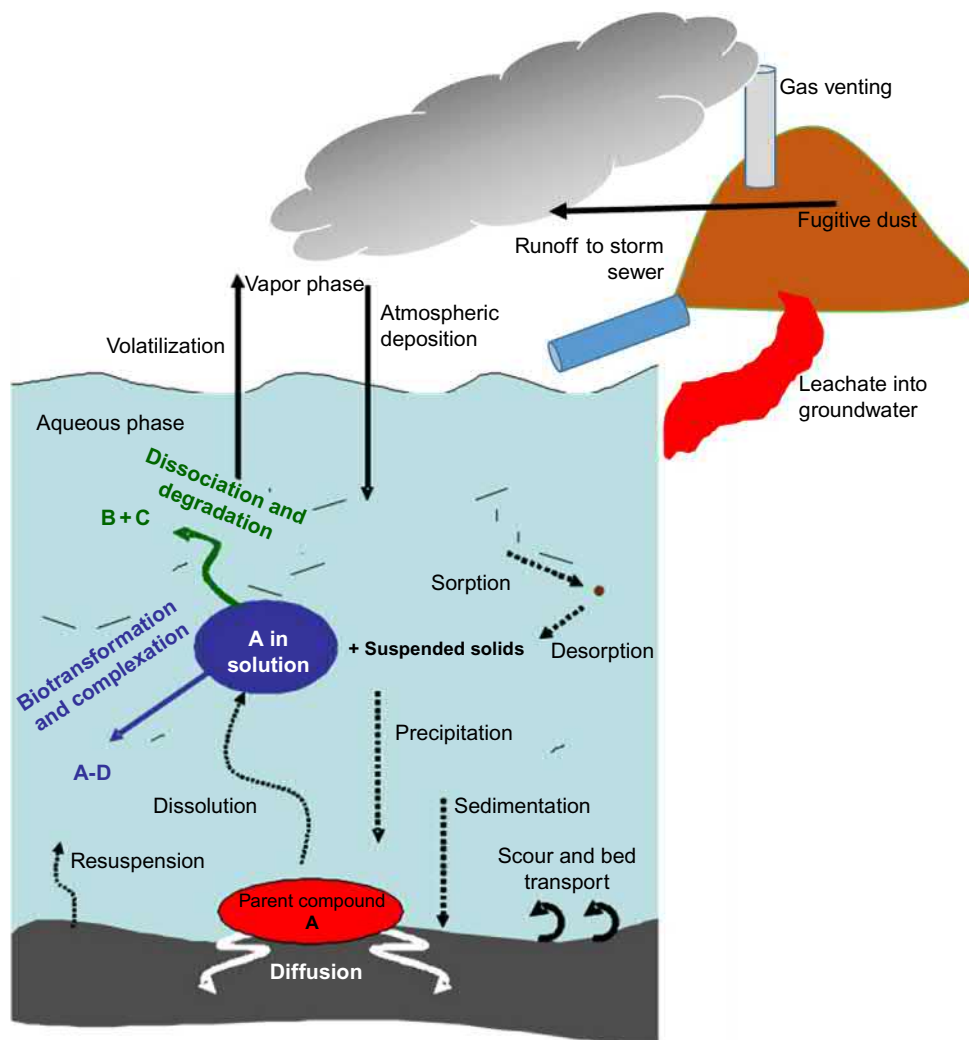
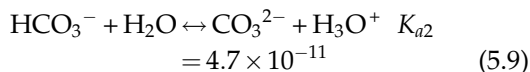


FIG. 5.11 Transport and transformation of chemicals in a water system. Contaminants from a landfill or other waste facility may reach a water system in various ways. Once the substance reaches the water, numerous transformation processes, including dissociation and degradation to form metabolites and degradation products (B, C and D), are brought about by both abiotic (e.g., hydrolysis and photolysis) and biotic (i.e., biodegradation) processes. *Adapted from W. Lyman, Transport and transformation processes, in: Rand GM Fundamentals of Aquatic Toxicology. Effects, Environmental Fate, and Risk Assessment, second ed., Taylor and Francis. Washington DC, 1995, pp. 449–492.*



Since K_{a1} is four orders of magnitude greater than K_{a2} , the second reaction can be ignored for the purposes of C equilibrium. The solubility of gases

in liquids can be described quantitatively by Henry's Law. Thus CO_2 in the atmosphere at 25°C , the Henry's Law constant, and the partial pressure can be applied to find the equilibrium. The K_H for $\text{CO}_2 = 29.4 \text{ atm mol}^{-1} \text{ L}$. The partial

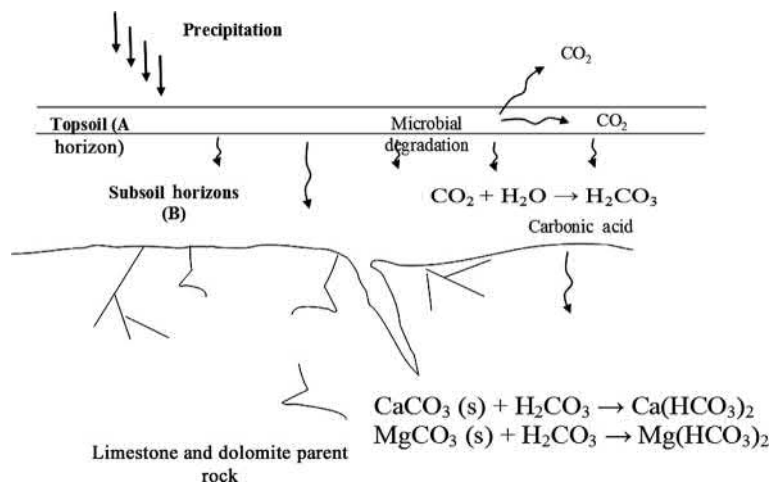


FIG. 5.12 Biogeochemistry of carbon equilibrium. The processes that release carbonates are responsible for much of the buffering capacity of natural soils against the effects of acid rain. Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999.

pressure of CO_2 is found by calculating the fraction of CO_2 in the atmosphere. Assuming a mean concentration of CO_2 in the earth's troposphere to be 350 ppm by volume in the atmosphere, the mole fraction of CO_2 is thus 3.5×10^{-4} and the partial pressure of CO_2 is then $3.5 \times 10^{-4} \text{ atm}$ (P is proportional to n as $PV = nRT$).

Thus the carbon dioxide and carbonic acid molar concentration can now be found from Henry's Law:

$$[\text{CO}_2] = [\text{H}_2\text{CO}_3] = 29.4 \text{ atm mol}^{-1} \text{ L} \times 0.000350 \text{ atm} = 1.2 \times 10^{-5} \text{ M}$$

The equilibrium is $[\text{H}_3\text{O}^+] = [\text{HCO}_3^-]$. Taking this and the previously calculated CO_2 molar concentration gives:

$$K_{a1} = 4.3 \times 10^{-7} = \frac{[\text{HCO}_3^-][\text{H}_3\text{O}^+]}{[\text{CO}_2]} = \frac{[\text{H}_3\text{O}^+]^2}{1.2 \times 10^{-5}}$$

$$[\text{H}_3\text{O}^+]^2 = 5.2 \times 10^{-12}$$

$$[\text{H}_3\text{O}^+] = 2.6 \times 10^{-6} \text{ M}$$

The log of 2.6×10^{-6} is -5.6 , so the negative log is 5.6. Or, the pH of the droplet is about 5.6.

Carbon dioxide, with water, is the ultimate product of aerobic microbial respiration, but it

is also an important greenhouse gas. From the preceding discussion, a global increase in CO_2 concentrations must also change the mean acidity of precipitation. For example, many models expect a rather constant increase in tropospheric CO_2 concentrations. For example, the increase from the 350 ppm to the present 400 ppm tropospheric CO_2 concentrations is accompanied by a proportional decrease in precipitation pH. The molar concentration can be adjusted using the previous equations:

$$3.4 \times 10^{-2} \text{ mol L}^{-1} \text{ atm}^{-1} \times 0.000400 \text{ atm} = 1.4 \times 10^{-5} \text{ M},$$

so

$$4.3 \times 10^{-7} = \frac{[\text{H}_3\text{O}^+]^2}{1.4 \times 10^{-5}}$$

and

$$[\text{H}_3\text{O}^+]^2 = 6.0 \times 10^{-12}$$

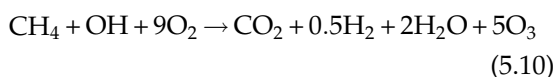
and

$$[\text{H}_3\text{O}^+] = 3.0 \times 10^{-6} \text{ M}$$

Thus average water droplet pH would decrease to about 5.5. This means that the incremental increase in atmospheric carbon dioxide can be expected to contribute to greater acidity in natural rainfall. The precipitation rates themselves would also be affected if greenhouse gas concentrations continue to increase, so any changes in atmospheric precipitation rates would also, on average, be expected to be more acidic. This is an interesting example of how the earth is actually a very large bioreactor. Changing one variable can profoundly change the entire system; in this instance the release of one gas changes numerous physical (e.g., temperature) and chemical (e.g., precipitation pH) factors, which in turn evoke a biological response (biome and ecosystem diversity).

Carbon dioxide is a prominent greenhouse gas, so it is logical to expect the increases in its atmospheric concentrations to be associated with changes in climate. Modeling climate change is difficult given the many drivers and constraints involved (see Fig. 5.13). The changes can affect biological systems. Ecological structure and function can be particularly sensitive. The effects can snowball or diminish as a result of the interactions of these drivers and constraints. For example, wetland structures may change if anaerobic microbial decomposition increase, which would result in increasing releases of CH₄, which would mean increasing global temperatures, all other factors being held constant. However, if greater biological activity and increased photosynthesis is triggered by the increase in CO₂, and wetland depth is decreased, CH₄ global concentrations would fall, leading to less global temperature rise. Conversely, if this increased biological activity and photosynthesis leads to a decrease in forest floor detritus mass, then less anaerobic activity may lead to lower releases of CH₄. In actuality, there will be increases and decreases at various scales, so the net effects on a complex, planetary system are highly uncertain.

Another important carbon-based greenhouse gas is methane (CH₄), which as mentioned is the product of anaerobic decomposition from myriad natural and human activities and facilities, such as from landfills. Methane also is emitted during the combustion of fossil fuels and cutting and clearing of forests. The concentration of CH₄ in the atmosphere has been steady at about 0.75 for over a thousand years, and then increased to 0.85 ppm in 1900. Since then, in the space of only a hundred years, has skyrocketed to 1.7 ppm. Methane is removed from the atmosphere by reaction with the hydroxyl radical (OH) as



This indicates that the reaction creates carbon dioxide, water vapor, and ozone, all of which are greenhouse gases, so the effect of one molecule of methane is devastating to the production of the greenhouse effect.

The difference in gas concentrations and the exchange coefficients between the atmosphere and surface waters determines how quickly a molecule of gas can move across the ocean-atmosphere boundary. It takes about one year to equilibrate CO₂ in the surface ocean with atmospheric CO₂, thus large atmosphere-ocean differences in CO₂ concentrations are common. Biota and ocean circulation account for the majority of the difference. The oceans contain vast C reservoirs, with which the atmosphere exchanges since CO₂ reacts with water to form carbonic acid and its dissociation products. With the increased atmospheric CO₂ concentrations, the interaction with the ocean surface alters the chemistry of the seawater resulting in ocean acidification [24, 25].

Ocean uptake of anthropogenic CO₂ is primarily a physical response to increasing atmospheric CO₂ concentrations. Increasing the partial pressure of a gas in the atmosphere directly above the body of water causes the gas to diffuse into that water until the partial pressures across the

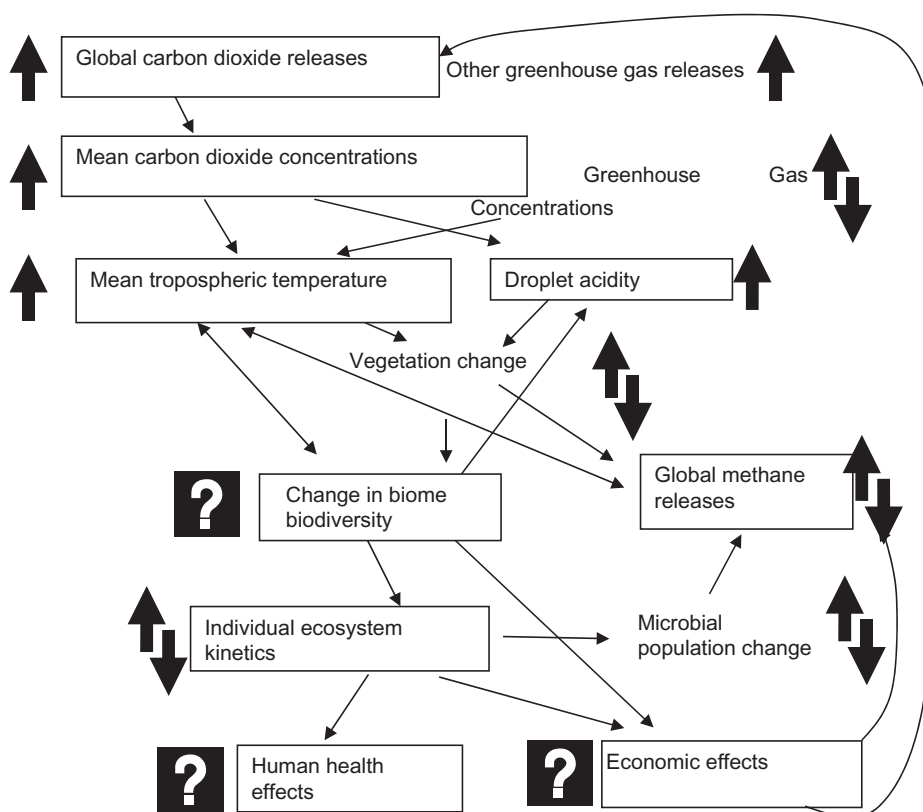


FIG. 5.13 Systematic view of changes in tropospheric carbon dioxide. Thick arrows indicate whether this factor will increase (up arrow), decrease (down arrow), or will vary depending on the specifics (e.g., some greenhouse gas releases have decreased, e.g., the chlorofluorocarbons, and some gases can cool the atmosphere, e.g., sulfate aerosols). Question mark indicates that the type and/or direction of change are unknown or mixed. Thin arrows connect the factors as drivers toward downstream effects. Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015.

air-water interface are equilibrated. The effects are complex, for example, increasing CO_2 also modifies the climate which in turn may change ocean circulation, which changes the rate of ocean CO_2 uptake. Marine ecosystem changes also alter the uptake. [25]

Halocarbons comprise the principal classes of compounds involved in the destruction of atmospheric ozone, but are also at work in promoting global warming. The most effective global warming gases are CFC-11 and CFC-12, both of which are no longer manufactured, and the

banning of these substances has shown a leveling off in the stratosphere.

Many, but not all, greenhouse gases are C-based. Nitrous oxide is emitted to the atmosphere predominantly as a result of human activities, especially the cutting and clearing of tropical forests, which are vital sources of atmospheric oxygen. The greatest problem with nitrous oxide is that there appear to be no natural removal processes for this gas and so its residence time in the stratosphere is quite long. This is prime example of the interrelationships

and interdependencies between the C and N cycles.

The cycling of C indicates the complexity of possible outcomes of waste management and engineering. For example, pollution control efficiency and success have often been based on CO₂ production rates, that is, the greater the amount of CO₂ leaving a landfill gas flare system, the more efficiently the pollution control equipment is operating. This is because complete combustion results in the production of only CO₂ and H₂O. Likewise, the production of CH₄ has been an indication of complete anaerobic digestion of organic compounds within the landfill. Unfortunately, both indicators of pollution control efficiency happen to be greenhouse gases, with CH₄ being 25 times more potent as a greenhouse gas than is CO₂.

5 NUTRIENT CYCLING

Nitrogen (N) and sulfur (S), along with phosphorous (P) and potassium (K), are considered to be macronutrients because plant life depends on them for survival and growth. However, from a waste management perspective, N and S compounds deserve special attention, given that many waste management facilities generate and release substantial amounts of N and S compounds into the environment.

Nitrate and nitrite compounds, as well as ammonia and amines are important water pollutants. Two of the six National Ambient Air Quality Standards (NAAQS) pollutants are oxides of these elements, that is, sulfur dioxide (SO₂) and nitrogen dioxide (NO₂). In addition, the oxides of nitrogen (NO_x), made up of NO₂ and nitric oxide (NO), are major precursors of another NAAQS pollutant, that is, ozone. However, some of these same and other nutrient compounds are essential for crops, woodlands, and other ecosystems.

In addition to N and S, the cycling of other nonmetals is also crucial to a complete

understanding of air pollution. In fact, P molecules are essential parts of energy transfer during photosynthesis. When P compounds deposit onto surface waters, the increased P concentrations accelerate eutrophication and, along with increasing N concentrations, contribute to the so-called dead zones in large water bodies, such as the Chesapeake Bay. In fact, P and K are intricately woven into the N and S cycles. P is a component of atmospheric deposition, along with N and S compounds. The P component is usually higher when wet deposition is greater than dry deposition, since P is usually bound to aerosols. Thus in areas where large amounts of P are applied as a fertilizer to land or in arid regions with strong winds to transport soils, airborne P can be substantial, albeit still less than airborne N [26]. Most of the total P in the atmosphere is in mineral form as aerosols, but there are also large global sources of P from biomass burning, and even less from energy and industrial combustion sources [27].

Phosphorous is also indirectly responsible for pollution, since the production of P fertilizer releases fluoride compounds. The movement of fluoride through the atmosphere and into a food chain illustrates an air-water interaction at the local scale (<100 km) [28]. Other industrial sources of fluoride include aluminum processing and glass manufacturing plants. Domestic livestock in the vicinity of substantial fluoride sources are exposed to fluoride by ingestion of forage crops. Fluoride released into the air by industry is deposited and accumulated in vegetation. Its concentration is sufficient to cause damage to the teeth and bone structure of the animals that consume the crops. Thus if a waste stream contains fluoride, the amount should be known by the waste manager.

Potassium is also part of the biogeochemistry of N and S. For example, when base cations like K deposited on soil and other surfaces, they increase surface's pH. This alkalinity buffers the acidity generated by N and S acidic compounds (e.g., H₂NO₃ and H₂SO₄, respectively).

5.1 The Nitrogen Cycle

Nitrogen is part of the abiotic and biotic parts of earth. The element exists in many chemical forms that move at varying rates in the nitrogen cycle. Like carbon, N is stored in reservoirs such as the atmosphere, living organisms, soils, and oceans [29]. From these sinks, N cycles between the biosphere and the atmosphere. The N cycles among ecosystems and the organisms, including humans, within these ecosystems. (Source: The source of this section is D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999.)

Most of the earth's mass of N resides in the atmosphere. Approximately 79% of the molecules in earth's atmosphere are molecular nitrogen (N_2). All organisms must metabolize N into larger molecules, notably amino acids, proteins, and deoxyribonucleic acid (DNA). Amino acids contain the functional group amine (NH_2) and are the building blocks of proteins. DNA is comprised of the nitrogenous bases, i.e., adenine, cytosine, guanine and thymine, which consist of rings of carbon and nitrogen atoms.

The N_2 is not directly available to most organisms (a major exception being the N-fixing bacteria found in legume roots). The atmospheric N_2 is converted to bioavailable N species (e.g., nitrates; NO_3^-) abiotically (e.g., lightning strikes or fires) and biotically (e.g., by the N-fixing bacteria known as diazotrophs).

Many ecosystems are N-limited as a result of N-limits of the flora and microorganisms living within these systems. Indeed, along with P, the amount of N is the major limiting factor on the rate of net primary production of biomass in most ecosystems. That is, an increase in bioavailable N is associated with an increase in production of biomass of these organisms in an ecosystem. For example, increasing the amount of carbon in a lake system will have little effect on the production of biomass, since most systems have ample mass of bioavailable C. Conversely, increasing bioavailable N in most lake

systems increases total biomass. Thus N is a limiting factor for plant growth.

The N-cycle mirrors the trophic state and energy cycles in ecosystems. Producers convert mineral forms of N to N-containing molecules, for example, amino acids and DNA. Consumers then receive N by consuming producers and forming even larger N-containing molecules, for example, proteins (built from amino acids). Higher trophic state consumers receive N from consuming lower level organisms, that is, both consumers and producers. Decomposers convert N in the opposite direction, that is, mineralization, converting the N-containing, organic molecules of dead organisms to inorganic compounds, for example, ammonium (NH_4^+) salts. The NH_4^+ salts have high aqueous solubility and readily absorb to soil particles. At these sites, bacteria and other microbes can oxidize the NH_4^+ into nitrite (NO_2^-) compounds and in turn to nitrate (NO_3^-) compounds. This oxidation process is known as nitrification. The NO_3^- compounds are quite bioavailable to most plant life (i.e., macrophytes). These dissolved oxidized forms of N are reduced (i.e., denitrified) by bacteria known as denitrifiers. This is a major process by which N is returned to the atmosphere.

Ionization is an important part of N and S cycling, as it is for all nutrient cycling. This is due to the configuration of electrons in an atom. The arrangement of the electrons in the atom's outermost shell, that is, valence, determines the ultimate chemical behavior of the atom. The outer electrons become involved in transfer to and sharing with shells in other atoms, that is, forming new compounds and ions. An atom will gain or lose valence electrons to form a stable ion that have the same number of electrons as the noble gas nearest the atom's atomic number. As mentioned, the N cycle includes three principal forms that are soluble in water under environmental conditions: the cation (positively charged ion) ammonium (NH_4^+) and the anions (negatively charged ions)

nitrate (NO_3^-) and nitrite (NO_2^-). Nitrates and nitrites then combine with various organic and inorganic compounds. Once taken into a plant, the NO_3^- is converted to NO_2^- . Since NO_3^- is soluble and readily available as a nitrogen source for plants (e.g., to form plant tissue such as amino acids and proteins), farmers are the biggest users of NO_3^- compounds in commercial fertilizers (although even manure can contain high levels of NO_3^-).

Nitrogen in several forms finds its way from the atmosphere to the soil through abiotic and biotic processes. As mentioned, NO_3^- compounds are formed from lightning and by nitrogen-fixing bacteria in legumes' root nodules. The Rhizobia (genera *Rhizobium*, *Sinorhizobium*, and *Bradyrhizobium*) are Gram-negative soil bacteria motile, rod-shaped, aerobic bacteria that infect legume roots (see Fig. 5.14) in a symbiotic relationship with legumes, for example, *Medicago*, *Melilotus*, and *Trigonella*. The symbiotic relationship results from the bacteria fixing atmospheric nitrogen, providing ammonium for protein production in the plant. In exchange, the bacteria obtain energy from the plant [30].

Nitrate compounds are also formed by microbial (fungal and bacterial) degradation of detritus by aerobes and anaerobes on the forest floor. With moisture, numerous simultaneous chemical reactions occur, making for a balance among various chemical forms of N (as well as those of S, P, K, C, and other nutrients). The chemical reactions in the N cycle, as in any nutrient cycle, require various energy sources, especially light, heat, and metabolic. Some biochemical processes with an organism fix molecular nitrogen (N_2) from the atmosphere, to form simple N-compounds (e.g., diazotrophs in root nodules), which in turn form amino acids in the tissues of plants and animals.

The mineralization and denitrification occurs by numerous processes, in addition to microbial degradation, including photolysis, hydrolysis, and reduction or oxidation. The result is a wide array of conversions of nitrogen-containing

organic compounds (e.g., proteins and amino acids) to inorganic (mineral) forms, such as ammonia, ammonium hydroxide, nitrite, and nitrate. Note that the gases at the top of Fig. 5.15 include those that are important in air pollution. For example, NO is one of the compounds involved in the photochemistry that leads to the formation of the pollutant ozone (O_3) in the troposphere. Note also that macrophytes are central in the figure. Much of the chemistry occurs on the floor in the detritus where microbes degrade complex molecules. Nutrients in the soil are transported by the roots' capillary action to plant cells. Gases are transpired through leaves back to the atmosphere.

The atmospheric speciation at the top of Fig. 5.15 is an oversimplification, with many competing processes. For example, soil NO_2^- compounds can release nitrous acid (HONO) directly to the atmosphere. When soil contains elevated amounts of nitrates due to fertilization, HONO is released to the atmosphere. The more acidic the soil the greater will be the release of HONO . In the troposphere, HONO leads to the formation of hydroxyl radicals, which both degrade and increase the deposition of air pollutants. Large volumes of acids are released from soil continuously to the atmosphere. Soils with high N concentrations form the acids from NO_2^- ions. These anions are first released into the soil by microbes that have transformed ammonium and nitrate ions into nitrite ions. Increasing soil acidity produces high nitrite concentrations, leading to greater concentrations of HONO emitted to the troposphere [31]. About 30% of the primary OH radical production is attributed to the photolysis of HONO .

Thus what may at first appear as a soil-water interaction (fertilizer added to increase crop yield) is indeed a soil-water-biota (microbial) process, followed by an air-water interaction (chemical transformation of air pollutants, followed by precipitation). In this instance, the air pollutants are decreased by increasing concentrations of water pollutants (nitrates and ammonium).



FIG. 5.14 The root nodules of a 4-week-old *Medicago italica* inoculated with *Sinorhizobium meliloti*. Source: Wikipedia photo; http://upload.wikimedia.org/wikipedia/commons/b/b3/Medicago_italica_root_nodules_2.JPG (accessed 03.10.09).

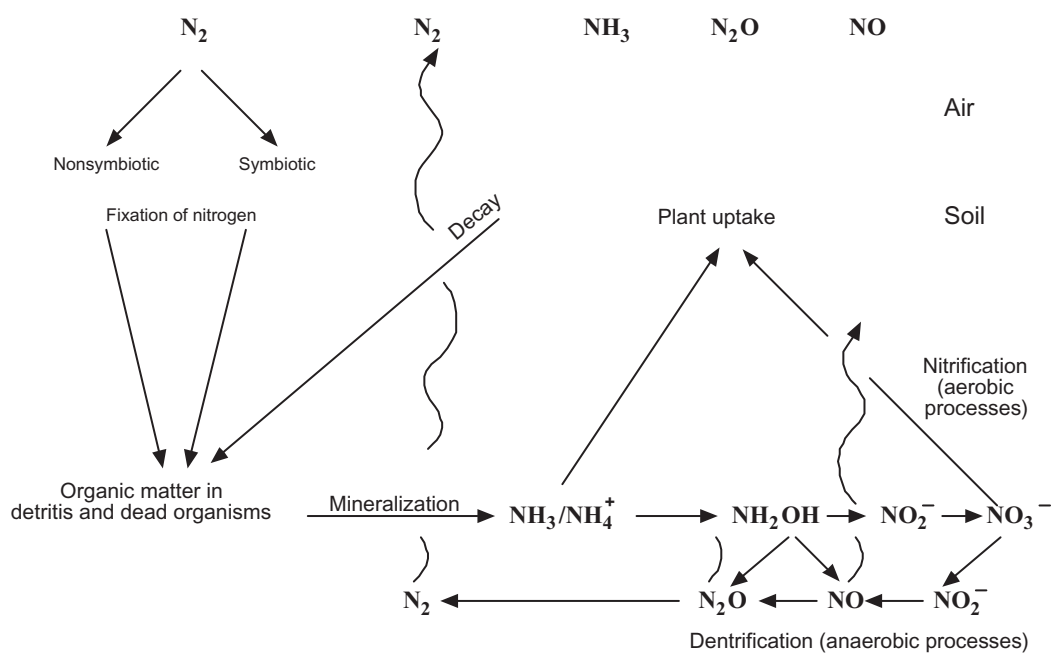


FIG. 5.15 Nitrogen cycling in the troposphere. Source: D.A. Vallero, *Environmental Contaminants: Assessment and Control*, Elsevier Academic Press, Burlington, MA, 2004.

Figure 5.15 also shows that when organic compounds are degraded by microbes, especially nitrifying bacteria, oxides of nitrogen (NO_x) are released to the atmosphere. Thus the flux of nitric oxide (NO) and nitrogen dioxide (NO_2) from the soil to the lower troposphere is inversely related to the rate of degradation of organic compounds in the soil.

Ion exchange is actually an example of sorption, that is, movement of a chemical species from the liquid or gas phase to the solid phase. Plants grow as a function of available nutrients and other cycles within the forest ecosystem [32]. With this growth, compounds of N and other nutrients find their way to the atmosphere.

¹Nitrogen has three common oxidation states, +3, +4, and +5. Like carbon, N can form many compounds, even with a single, other element. For example, it can combine with oxygen to form N_2O , NO, NO_2 , or N_2O_5 , all important air pollutants or precursors to air pollutants.

Nitrite is an intermediate compound in both nitrification and denitrification. The N in the nitrate anion (NO_3^-) has an oxidation state of +5 (i.e., three O atoms each with -2 charge plus 5 yields the nitrate charge of -1). The nitrite anion has a trivalent N, that is, N^{3+} (i.e., two O atoms each with -2 charge plus 3 yields the nitrite charge of -1). The major mechanism for producing N^{3+} in soil is by biological nitrification and denitrification processes. Nitrifying microbes produce nitrite ions from ammonium. Denitrifying microbes produce nitrite from nitrate [31].

The N compounds enter the troposphere by several mechanisms. In addition to the ordinary concentrations of molecular N, various nitrogen compounds are formed from reactions ranging from very fast (especially combustion) to quite slow, multistage (microbial) reaction rates. The two principal air pollutants regulated

throughout the world are nitric oxide and nitrogen dioxide. Nitric oxide (NO) is a colorless, odorless gas and is essentially insoluble in water. Nitrogen dioxide (NO_2) has a pungent acid odor and is somewhat soluble in water.

Air pollution experts now refer to NO and NO_2 collectively as NO_x . This is in part because the NO lifetime after emission is quite short ($>\text{minute} < \text{hour}$) [33]. The simple oxidation of molecular N at high temperature is:



The emitted NO rapidly undergoes photochemical transformation to NO_2 :



Indeed, NO and NO_2 can interconvert, depending on redox and photochemical conditions in the troposphere and stratosphere. For example, in sunlight, ultraviolet radiation splits NO_2 into NO and O. So, it is often preferred to consider the dynamic relationship of the two molecules rather than to ascribe a single speciation, especially for characterizing the atmosphere. However, the two compounds must be distinguished in risk assessments given their very different health effects.

Mobile sources (i.e., cars, trucks, trains, boats, and aircraft) comprise the largest contributor to NO_x emissions in the United States (59%; 11.3Mt., i.e., 12.7 million US tons in 2002). The U.S.'s largest contributing stationary source category is electric generation (22%; 4.2Mt. or 4.6 million tons in 2002), followed by industrial factories (11%; 2.2Mt. or 2.4 million tons in 2002). The eastern and midwestern U.S. regions had the highest emissions (see Fig. 5.16). Europe has similar emission profiles for NO_x (see Fig. 5.17), with the largest percentage coming from mobile sources (road and nonroad transport), and the largest stationary source being energy production and distribution.

Although both NO and NO_2 can be harmful to humans and ecosystems, NO is also actually

¹ Movement of a chemical species from solid to liquid phase is dissolution. Movement from the solid phase to gas phase is volatilization.

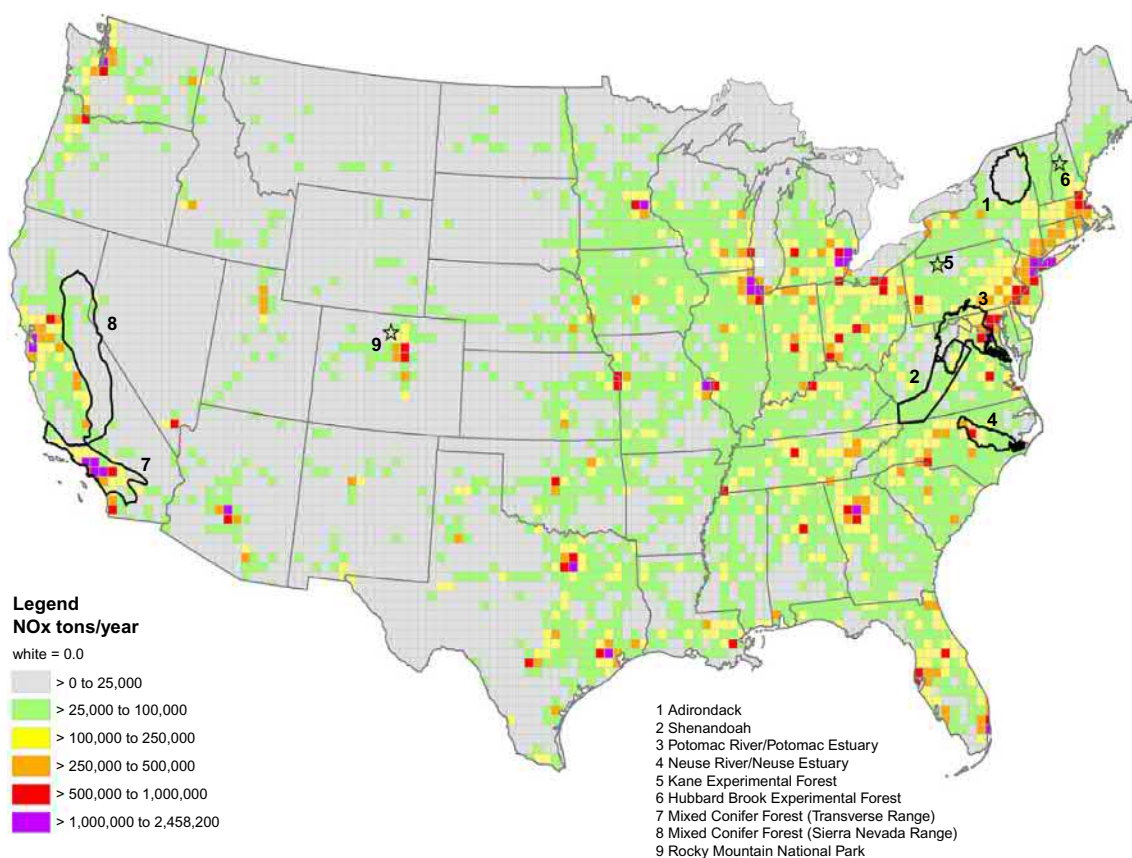


FIG. 5.16 Total oxides of nitrogen (NO_x) emissions (tons yr⁻¹) in 2002. Source: U.S. Environmental Protection Agency, Policy Assessment for the Review of the Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Oxides of Sulfur, EPA-452/R-11-005a, Research Triangle Park, NC, 2011.

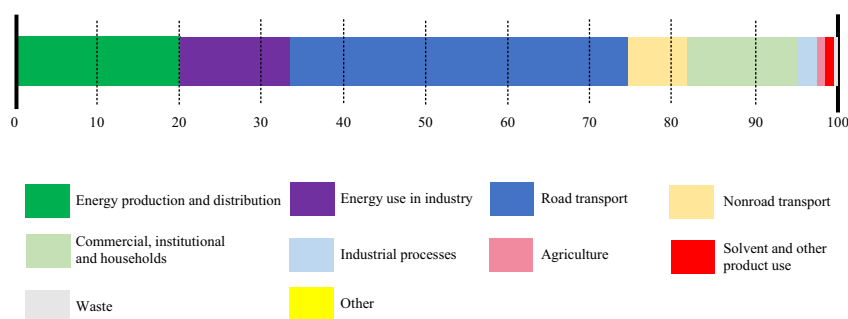
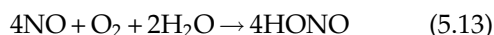


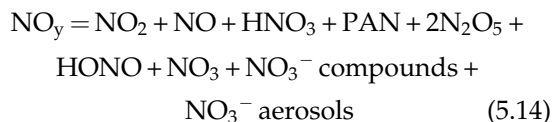
FIG. 5.17 European Union nations' percentage contribution to nitrogen (NO_x) emissions by industrial sector in 2010. Data from European Environmental Agency, Air Pollution Statistics, European Commission Eurostat, 2013. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Air_pollution_statistics (accessed 12.12.13).

essential to metabolism, so is harmful at much higher concentrations than that of NO_2 . On the other hand, NO_2 is inherently toxic, causing respiratory problems. Both compounds are precursors to tropospheric ozone formation, so present indirect health problems when the smog and O_3 are inhaled.

Nitrogen species important to air quality include many compounds in addition to NO_x . Atmospheric N reactions can be more complicated than may be inferred from reactions (5.11), (5.12). For example, the NO_x reaction from NO to NO_2 likely involves water and an intermediate, that is, nitrous acid (HONO):



The larger suite of N air pollution compounds is known as total reactive nitrogen, which is denoted as NO_y . This suite includes NO and NO_2 , plus their oxidation products [34]. The major vapor-phase and particulate constituents of NO_y include NO, NO_2 , nitric acid (HNO_3), peroxyacetyl nitrate (PAN), HONO, organic nitrates, and particulate nitrates:



Every NO_y compound is derived directly from NO_x emissions or through transformations in the troposphere [35]. Most of the compounds originate from combustion processes. As noted, the atmosphere itself is the source of much of the nitrogen leading to the formation of nitrogen compounds. Molecular nitrogen (N_2) makes up the largest share of gaseous content of the earth's atmosphere (79% by volume). Because N_2 is relatively nonreactive under most atmospheric conditions, it seldom enters into chemical reactions, but under pressure and at very high temperatures, such as in an internal combustion engine or industrial boiler, the molecular N will react with O_2 , that is, reaction (5.11).

This N_2 precursor is known as "thermal NO_x " since the oxides form at high temperatures, such as near burner flames in combustion chambers. Approximately 90%–95% of the nitrogen oxides generated in combustion processes are in the form of NO. Other nitrogen oxides can also form at high heat and pressure, especially NO_2 . Most motor vehicles around the world still employ high temperature/high pressure internal combustion engines. Thus such mobile sources contribute largely to the tropospheric concentrations of NO_x , making it a major mobile source air pollutant in terms of human health directly (e.g., respiratory toxicity of NO_2) and indirectly (i.e., NO_x as the key components in tropospheric ozone production). These conditions of high temperature and pressure can also exist in boilers such as those in power plants, so NO_x is also commonly found in high concentrations leaving fossil fuel power generating stations.

In addition to the atmospheric molecular nitrogen as a precursor of nitrogen air pollutants of combustion, fossil fuels themselves contain varying concentrations of N. Nitrogen oxides that form from the fuel or feedstock are called "fuel NO_x ." Unlike the sulfur compounds, which mainly exit stationary source stacks as vapor-phase compounds (e.g., SO_2 and other oxides of sulfur), a significant fraction of the fuel nitrogen burned in power plants and other stationary sources remains in the bottom ash or in unburned aerosols in the gases leaving the combustion chamber, that is, the fly ash. Nitrogen oxides can also be released from nitric acid plants and other types of industrial processes involving the generation and/or use of nitric acid (HNO_3).

At temperatures far below combustion, such as those often present in the ambient atmosphere, NO_2 can form the molecule $\text{NO}_2\text{-O}_2\text{N}$ or simply N_2O_4 that consists of two identical simpler NO_2 molecules. This molecular configuration is known as a dimer. The dimer N_2O_4 is distinctly reddish-brown and contributes to

the brown haze that is often associated with photochemical smog incidents.

In addition to the health effects associated with NO_2 exposure, much of the concern for regulating emissions of nitrogen compounds is to suppress the reactions in the atmosphere that generate the highly reactive molecule ozone (O_3). Nitrogen oxides play key roles in O_3 formation. Ozone forms photochemically (i.e., the reaction is caused or accelerated by light energy) in the lowest level of the atmosphere, known as the troposphere, where people live. Nitrogen dioxide is the principal gas responsible for absorbing sunlight needed for these photochemical reactions. So, in the presence of sunlight, the NO_2 that forms from the NO incrementally stimulates the photochemical smog-forming reactions because nitrogen dioxide is very efficient at absorbing sunlight in the ultraviolet portion of its spectrum. This is why ozone episodes are more common in the summer and in areas with ample sunlight. Other chemical ingredients, that is, ozone precursors, in O_3 formation include volatile organic compounds (VOCs), and carbon monoxide (CO). Governments regulate the emissions of precursor compounds to diminish the rate at which O_3 forms.

Cyanide (CN^-) is another N anion that is important to air pollution. Cyanide in the bloodstream impairs oxidative phosphorylation, a process by which oxygen is taken up for the production of essential cellular energy in the form of adenosine triphosphate (ATP). This process transfers electrons from nicotinamide adenine dinucleotide (NADH) to form water from H^+ and O_2 , through a series of reactions catalyzed by enzymes. With less O_2 available for the cytochrome C to react with and hence complete the electron transport process, ATP production is diminished. The high binding affinity of CN^- to the ferric ion in hemoglobin is responsible for the decrease in O_2 carried in the blood. Thus CN^- binds preferentially to hemoglobin and prohibits oxygen binding.

Methemoglobinemia is a particularly troublesome outcome resulting from endogenous production of the CN^- anion results from the

exposure of infants to nitrates. Ingesting high concentrations of nitrates, for example, in drinking water can cause serious short-term illness and even death in infants 6 months or younger. The serious illness in infants is due to the conversion of microbial NO_3^- to NO_2^- in the gastrointestinal tract. Small children's lower stomach acidity (greater pH) allows for bacterial growth that does not grow in adult stomachs. Also, NO_3^- is more easily converted to NO_2^- in the hemoglobin of young children than in adult hemoglobin, because the circulatory system is too mature in small children to for the O_2 to displace the nitrate and to return to normal hemoglobin. Small children are also susceptible given their greater fluid intake to body weight ratio compared to adults, as well as lower enzyme levels needed to convert methemoglobin to hemoglobin [36]. As a result, the increased NO_2^- concentrations interfere with the oxygen-carrying capacity of the blood. Especially in small children, when nitrates compete successfully against molecular oxygen, the blood carries methemoglobin (as opposed to healthy hemoglobin), giving rise to clinical symptoms. This acute condition can deteriorate a child's health rapidly over a period of days, especially if the water source continues to be used. Long-term, elevated exposures to nitrates and nitrites can cause an increase in the kidneys' production of urine (diuresis), increased starchy deposits, and hemorrhaging of the spleen. [37]

A few animal studies suggest that elevated NO_3^- and NO_2^- in exposures may also elicit other effects, for example, increased miscarriage rates and anencephaly. Nitrate exposure may also cause hypothyroidism (i.e., by mimicking and blocking iodide from reaching the thyroid). [38]

5.2 Interactions Between Sulfur and Nitrogen

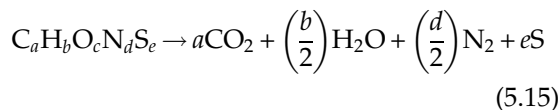
From the standpoint of air pollution, the biogeochemical cycles must not be limited to single elements. As shown in Fig. 5.18, after a compound

is emitted it reacts with numerous other compounds and changes physically and chemically. It is transported advectively, is dispersed, and finally deposited to the earth's surface, where it continues to undergo physical, chemical, and biological changes. This is demonstrated by the interactions of N and S in acid deposition, as well as by the integration of myriad atmospheric chemical species that influence and are influenced by N and S [35]. This includes both the formation of conventional NAAQS pollutants, like ozone and particulate matter, as well as the transformation and changes in bioavailability of toxic air pollutants, for example, mercury (Hg) and semivolatile organic compounds (SVOCs) like dioxins and organochlorine pesticides.

The atmospheric movement of N and S compounds and other pollutants from sources to receptors is only one form of translocation. A second one involves the attempt to control air pollutants at the source. For example, the control of SO₂ and particulate matter by wet or dry scrubbing techniques yields large quantities of waste materials—often toxic—which are subsequently stored on-site at the facility or taken to landfills and other long-term disposal sites. If these wastes are not properly stored, they can be released to soil or water systems, for example, from runoff of acids. The prime examples involve the disposal of toxic materials in dump sites or landfills. The Resource Conservation and Recovery Act of 1976 and subsequent revisions are examples of legislation to ensure proper management of solid waste disposal and to minimize damage to areas near landfills (see [Chapter 2](#)).

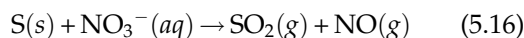
The oxidized chemical species of sulfur and nitrogen [e.g., sulfur dioxide (SO₂) and nitrogen dioxide (NO₂)] form acids when they react with water. This can occur in any media, for example, the atmosphere (i.e., acid deposition) and in mining waste and ash runoff to surface waters and groundwater. The lowered pH is responsible for numerous environmental problems. Many compounds contain both N and S along with the typical organic elements (C, H, and

O). The reaction for the combustion of such compounds, in general form, is:



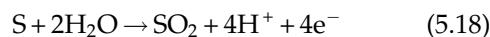
[Reaction \(5.15\)](#) demonstrates the incremental complexity as additional elements enter the reaction. In the real world, pure reactions are rare. The environment is filled with mixtures and heterogeneous reactions. Reactions can occur in sequence, parallel, or both. For example, a feedstock to a municipal incinerator contains myriad types of wastes, from garbage to household chemicals to commercial wastes, and even small (and sometimes) large industrial wastes that may be illegally dumped. The N-content of typical cow manure is about 5 kg per metric ton (about 0.5%). If the fuel used to burn the waste also contains S along with the organic matter, then the five elements will react according to the stoichiometry of [reaction \(5.15\)](#).

Certainly, combustion specifically and oxidation generally are very important processes that lead to N and S pollutants. But they are certainly not the only ones. As mentioned, oxidation and reduction of N and S occur in ecosystems as represented by trophic state and energy levels. The formation of sulfur dioxide (SO₂) and nitric oxide (NO) by acidifying molecular sulfur is a redox reaction:



The designations in parentheses give the physical phase of each reactant and product: “s” for solid, “aq” for aqueous, and “g” for gas.

The oxidation half-reactions for this reaction are as follows:



The reduction half-reactions for this reaction are as follows:

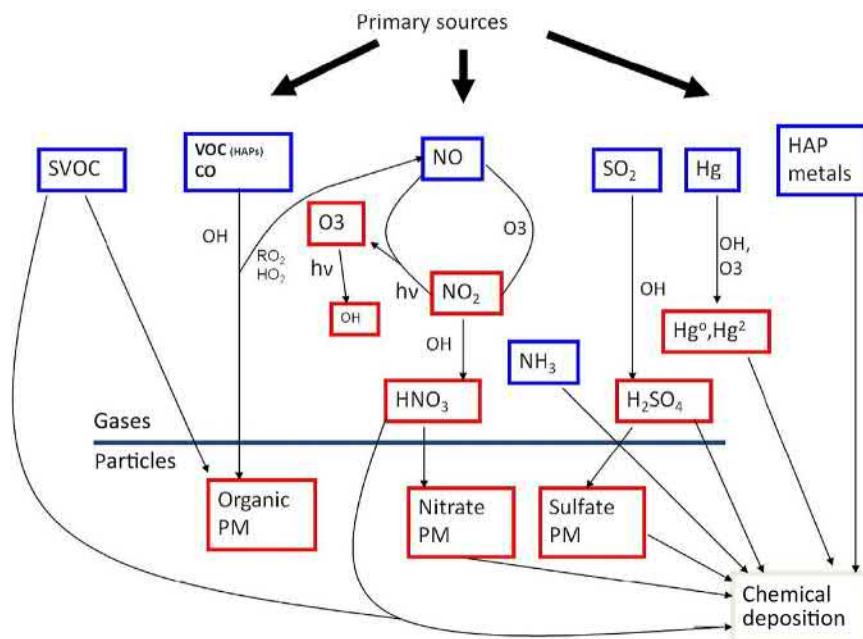
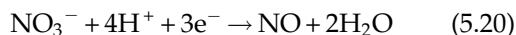
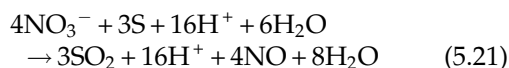


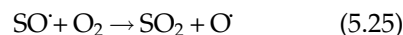
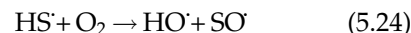
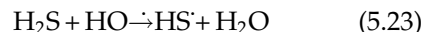
FIG. 5.18 Interactions between nitrogen and sulfur compounds, and among S and N compounds and other air pollutants. Notes: SVOC, semivolatile organic compound; VOC, volatile organic compound; RO₂, radical consisting of a chain of organic compounds with H substituted with O₂ (e.g., propane, C₃H₈, reacts with OH to form the radical, C₃H₇O₂); Hg, mercury. Source: U.S. Environmental Protection Agency, Policy Assessment for the Review of the Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Oxides of Sulfur, EPA-452/R-11-005a, Research Triangle Park, NC, 2011.



Therefore the balanced oxidation-reduction reactions are as follows:



sulfide, or oxidized forms, for example, sulfur dioxide (see Fig. 5.19). Both forms include air pollutants. Hydrogen sulfide is oxidized to sulfur dioxide in a three-step process. Note that the hydroxyl radical initiates the transformation from hydrogen sulfide to sulfur dioxide:



5.3 The Sulfur Cycle

Compounds of sulfur (S), as those of N, exist at atmospheric concentrations well in excess of what would be expected from equilibrium geochemistry in an atmosphere with 21% O₂ [39]. Sulfur is released to the atmosphere as either reduced forms, for example, hydrogen

The atmospheric reactions of SO₂ are very complex and proceed through three different pathways to the sulfate ion (SO₄²⁻). Sulfur dioxide can react with the hydroxyl radical to form the HSO₃ radical, which then can react with another hydroxyl radical to form water and SO₃ or

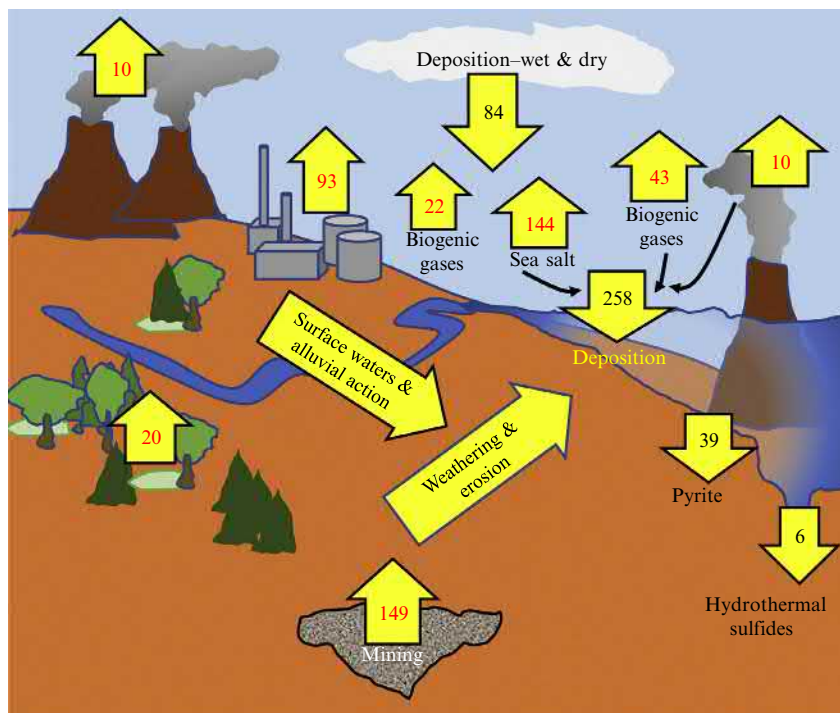
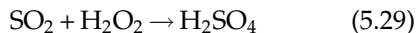
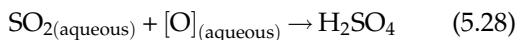
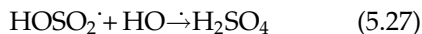


FIG. 5.19 Fluxes of sulfur to and from the atmosphere (teragrams of S in arrows). Data from R. Foust. (2004). *Atmospheric reactions of sulfur and nitrogen*. Available: http://jan.ucc.nau.edu/~doetqp-p/courses/env440/env440_2/lectures/lec37/lec37.htm.

H_2SO_4 . Sulfur dioxide has sufficient aqueous solubility to dissolve in water droplets where it can react with oxygen gas to form SO_4^{2-} . The third pathway to sulfate occurs when sulfur dioxide reacts with hydrogen peroxide to form sulfuric acid:



With sufficient residence time in the atmosphere, S will be oxidized to the sulfate ion, usually as sulfuric acid (H_2SO_4). Ammonia (NH_3), the most common base in the atmosphere, reacts with H_2SO_4 to form ammonium bisulfate (NH_4HSO_4)

and ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$). Sulfuric acid, NH_4HSO_4 , and $(\text{NH}_4)_2\text{SO}_4$ all are hygroscopic substances, that is, readily dissolved in water. Thus they wash out of the atmosphere during precipitation events. [40]

A reduced form of sulfur that is highly toxic and an important pollutant is hydrogen sulfide (H_2S). Certain microbes, especially bacteria, reduce nitrogen and sulfur, using the N or S as energy sources through the acceptance of electrons. For example, sulfur-reducing bacteria can produce hydrogen sulfide (H_2S), by chemically changing oxidized forms of sulfur, especially sulfates (SO_4). To do so, the bacteria must have access to the sulfur, that is, it must be in the water, which can be in surface or groundwater, or the water in soil and sediment. These sulfur reducers are often anaerobes, that is, bacteria that live in water where

concentrations of molecular oxygen (O_2) are deficient. The bacteria remove the O_2 molecule from the sulfate leaving only the S, which in turn combines with hydrogen (H) to form gaseous H_2S .

In groundwater, sediment, and soil water, H_2S is formed from the anaerobic or nearly anaerobic decomposition of deposits of organic matter, for example, plant residues. Thus redox principles can be used to treat H_2S contamination, that is, the compound can be oxidized using a number of different oxidants (see Table 5.5). Strong oxidizers, like molecular oxygen and hydrogen peroxide, most effectively oxidize the reduced forms of S, N, or any reduced compound.

Sulfur is also an important component of particulate matter (PM; see Table 5.6). For example, diesel particulate matter is formed by a number of simultaneous physical processes during cooling and dilution of exhaust, that is, nucleation, coagulation, condensation, and adsorption.

TABLE 5.5 Theoretical Amounts of Various Agents Required to Oxidize 1 mg L^{-1} of Sulfide Ion

Oxidizing Agent	Amount/ (mg L^{-1}) Needed to Oxidize 1 mg L^{-1} of S^{2-} Based on Practical Observations	Theoretical Stoichiometry (mg L^{-1})
Chlorine (Cl_2)	2.0–3.0	2.2
Chlorine dioxide (ClO_2)	7.2–10.8	4.2
Hydrogen peroxide (H_2O_2)	1.0–1.5	1.1
Potassium permanganate ($KMnO_4$)	4.0–6.0	3.3
Oxygen (O_2)	2.8–3.6	0.5
Ozone (O_3)	2.2–3.6	1.5

Source: Water Quality Association, Ozone Task Force Report "Ozone for POU, POE & Small Water System Applications," Lisle, Illinois, 1999.

The core of the particles is formed by nucleation and coagulation from primary spherical particles consisting of solid carbonaceous matter (known as elemental carbon; EC) and ash (metals and other elements). By coagulation, adsorption, and condensation, various organic and S compounds (e.g., sulfates) are added and combined with other condensed material [41].

The small diameter of diesel PM ($<0.5 \mu\text{m}$) makes for very large surface areas. $<0.5 \text{ mm}$, these particles have a very large surface area per gram of mass, which allows them to adsorb large quantities of ash, organic compounds, and sulfate (see Fig. 5.20). The specific surface area of the EC core is approximately $30\text{--}50 \text{ m}^2 \text{ g}^{-1}$. The organic constituents originate from unburned fuel, engine lubrication oil, and small quantities of partial combustion and pyrolysis products. During combustion, S compounds in the fuel are oxidized to sulfur dioxide (SO_2). From 1%–4% of fuel S is oxidized to form H_2SO_4 . Upon cooling, this sulfuric acid and water condense into an aerosol that is nonvolatile under ambient conditions [41].

Thus N and S compounds are ubiquitous in the atmosphere and the environment. They are constituents of both essential and detrimental compounds. As such, their complete

TABLE 5.6 Typical Chemical Composition (Percent) of Fine Particulate Matter ($PM_{2.5}$)

	Eastern U.S.	Western U.S.	Diesel $PM_{2.5}$
Elemental carbon (%)	4	15	75
Organic carbon (%)	21	39	19
Sulfate, nitrate, ammonium (%)	48	35	1
Minerals (%)	4	15	2
Unknown (%)	23	–	3

Source: U.S. Environmental Protection Agency, Air Quality Criteria for Particulate Matter, External review draft, 1999.

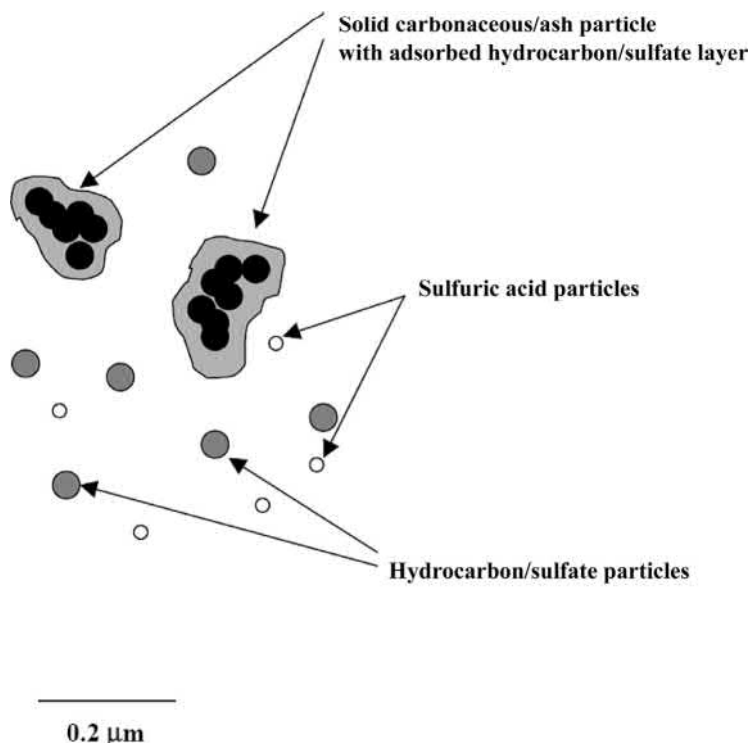


FIG. 5.20 Diesel particulate matter. Source: U.S. Environmental Protection Agency, *Health Assessment for Diesel Engine Exhaust*. Report No. EPA/600/8-90/057F, National Center for Environmental Assessment, Washington, DC, 2002.

biogeochemical cycles must be understood to explain the formation and fate of air pollutants.

6 BIOGEOCHEMICAL CYCLES AND DECISION MAKING

Waste management decisions are often made among competing interests and perspectives. These involve trade-offs. For example, remediating a contaminated site, may call for excavation of soil, which is then incinerated. The complete incineration will result in generating and emitting greenhouse gases. Determining whether this approach is successful and appropriate depends on the extent and quality of options from which these emissions occur. For example,

if dioxin-laden soil is incinerated, this may have been the only viable approach to detoxify a very toxic and persistent compound. Releasing CO₂ in this case is truly a measure of success.

One of the biggest engineering challenges is how to select and operate control technologies in a manner fully cognizant and deferential of the biogeochemical cycles. This view can support work to reduce the impact of global climate change debate, in light of the seeming paucity of ways to deal with the problem. The National Academy of Engineering has identified the most important challenges to the future of engineering. Both the nitrogen and carbon biogeochemical cycles are explicitly identified among the most pressing engineering needs.

The biogeochemical cycle that extracts nitrogen from the air for its incorporation into plants—and hence food—has become altered by human activity. With widespread use of fertilizers and high-temperature industrial combustion, humans have doubled the rate at which nitrogen is removed from the air relative to pre-industrial times, contributing to smog and acid rain, polluting drinking water, and even worsening global warming. Engineers must design countermeasures for nitrogen cycle problems, while maintaining the ability of agriculture to produce adequate food supplies [42–44]. The C cycle and nutrient cycles are inextricably linked. Like C, as discussed in the next chapter, chemical species of N and the other nutrient elements are essential and toxic, depending on its dose and form. The Academy articulates this challenge:

The biogeochemical cycle that extracts nitrogen from the air for its incorporation into plants—and hence food—has become altered by human activity. With widespread use of fertilizers and high-temperature industrial combustion, humans have doubled the rate at which nitrogen is removed from the air relative to pre-industrial times, contributing to smog and acid rain, polluting drinking water, and even worsening global warming. Engineers must design countermeasures for nitrogen cycle problems, while maintaining the ability of agriculture to produce adequate food supplies. [45]

Engineers can expect to be increasingly asked to recommend improvements to the biogeochemical cycling of C, such as enhancements to the food life cycles (e.g., animal feeding operations, farmlands, rangelands, and groceries). How can engineering innovation improve the efficiency of various human activities related to nitrogen, from making fertilizer to recycling food wastes? Currently, less than half of the fixed nitrogen generated by farming practices actually ends up in harvested crops. And less than half of the nitrogen in those crops actually ends up in the foods that humans consume. In

other words, fixed nitrogen leaks out of the system at various stages in the process—from the farm field to the feedlot to the sewage treatment plant. Engineers not only need to identify the leakage points and devise systems to plug them, that is, the structural and mechanical solutions, but must engage biological solutions, such as understanding the processes that lead to increased C and nutrient emissions, and applying this understanding to modify the processes accordingly [46].

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Mine Waste: A Brief Overview of Origins, Quantities, and Methods of Storage[☆]

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OUTLINE

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1 ORIGINS AND QUANTITIES OF MINE WASTE

With an expanding world market for mineral commodities such as chrome, coal, copper, diamonds, fluorspar, gold, iron, manganese, and

zinc, so necessary for the functioning of the modern world, mining companies are exploiting ever low-grade ore bodies on an ever-increasing scale. Mining on a vast scale is usually necessary for profitability of a lower-grade mine, and volumes of waste are commensurately large.

The actual volume of mine waste in need of disposal in dumps and tailings storage facilities, worldwide, is difficult to assess. In 1996 the International Commission on Large Dams (ICOLD) [1] estimated that this “almost

[☆] The first edition of this chapter was written by Professor Geoff Blight. Professor Blight passed away on November 7, 2013. Dr. Vallero has only slightly modified the text from the first edition. In addition, two boxes have been added to address recent mine waste issues.

certainly" exceeds $5 \times 10^9 \text{ t year}^{-1}$ (5 billion tonnes per year). Considering that some valuable commodities occur in their ores in concentrations of grams or carats per tonne (1 carat=0.2g, 1t=1000kg), and that many individual mines extract ore in excess of $5 \times 10^7 \text{ t year}^{-1}$ (even the estimate of ICOLD is probably too low). For example, a single platinum tailings storage at Rustenburg, South Africa has a storage capacity of almost $1 \times 10^9 \text{ t}$ over a life of 50years [2]. The mine currently sends $0.5 \times 10^6 \text{ t}$ of tailings to storage every month and plans to increase this to $2 \times 10^6 \text{ t}$ every month.

More recent estimated quantities of mine waste are as follows:

- The world's iron, copper, gold, lead, and bauxite (aluminum) mines together generated $35 \times 10^9 \text{ t}$ of waste in 1995 alone [3].
- The South African gold mining industry produced $7.4 \times 10^5 \text{ t}$ of gold tailings in the decade from 1997 to 2006, that is, $7.4 \times 10^4 \text{ t year}^{-1}$ [4].
- All gold mining waste produced in the past century in South Africa amounts to $6 \times 10^9 \text{ t}$, which covers a total area of 400–500 km², and contains $4.30 \times 10^5 \text{ t}$ of uranium and $3.0 \times 10^4 \text{ t}$ of sulfur, both of which, and especially the sulfur, have a high pollution potential [5].

The term "mine waste storage" is preferred to the more common "mine waste disposal," because advances in extractive metallurgy, along with increased demand and price for a commodity periodically coincide to allow a particular mine waste deposit to be reworked and further resources to be extracted from it at a profit. As examples, some gold mine waste storages in South Africa have been remined and reprocessed three times in the past 100years. Some of these deposits started out as waste rock which was unprofitable to process at the time, but was necessary to remove to access richer ores. Some platinum mines are now considering reprocessing their older tailings storages for platinum and other minerals, and coal mines are reprocessing

their old coal discard storages. Thus there is a realization that mine waste deposits are really storages of low-grade ore. They do not consist of the waste they were formerly considered to be. Even if the grade of mineral they contain remains too low for economical extraction, there may be a present or future economic value for other minerals in what is presently waste, or as a construction material.

It is for this reason that there is a great reluctance in the mining industry to "dispose" of waste by placing it in locations that render the waste inaccessible for future reprocessing, for example, in "worked out" parts of a mine, except where it can be used for strata support. In time to come, not only may the waste become profitable to reprocess but the stopes themselves may also be worth remining to remove seams or reefs of ore previously regarded as uneconomical to mine.

Ore bodies usually contain more than one type of mineralization. As examples, ore mined primarily for its platinum content, usually also contains chrome, used in stainless steel manufacture, and apatite from which phosphate fertilizers can be produced. At least one platinum mine in South Africa also extracts chrome as a by-product and supports a phosphoric acid plant for fertilizer manufacture. Another example relating to by-products is the South African gold mining industry which produced uranium as a by-product, much of which contributed to the Hiroshima and Nagasaki bombs during World War II. This activity stopped in the mid-1960s when the price of uranium fell, but it is now starting up again as it is being realized that nuclear power will have to be used in the future to replace dwindling coal and oil supplies. Fig. 6.1 shows a dump of waste sand, from early mining operations (1885–1905), in the process of being removed for reprocessing to extract gold and uranium left in the sand after the initial extraction process, 100 years ago.

Some mine waste can be recycled for other purposes. For example, waste rock can be used as a fill material in civil engineering works, or



FIG. 6.1 A 100-year-old dump of gold tailings sand being remined for processing to extract the uranium and residual gold content.

if the rock is sound, durable, and unweathered and has a satisfactory mineralogy, as aggregate for concrete and in asphalt and road layer works. Gypsum, a by-product of fertilizer manufacture from apatite rock, can be used to make building boards or can be reprocessed to produce sulfuric acid and building cement.

2 WASTE CHARACTERISTICS

Mine waste may arise in a number of forms: as stripped soil and coarse, broken, partly weathered rock overburden in open cast or strip-mining operations; as unweathered development waste rock in underground mining; and as fine-grained tailings, the residuum of the process of comminution and mineral extraction from ores. The various wastes are usually stored separately. The top soil is stock piled for eventual use in environmentally rehabilitating the dumps of coarse wastes or the surfaces of back-filled surface-mining voids. The coarse broken rock is usually stored in dumps, either with or

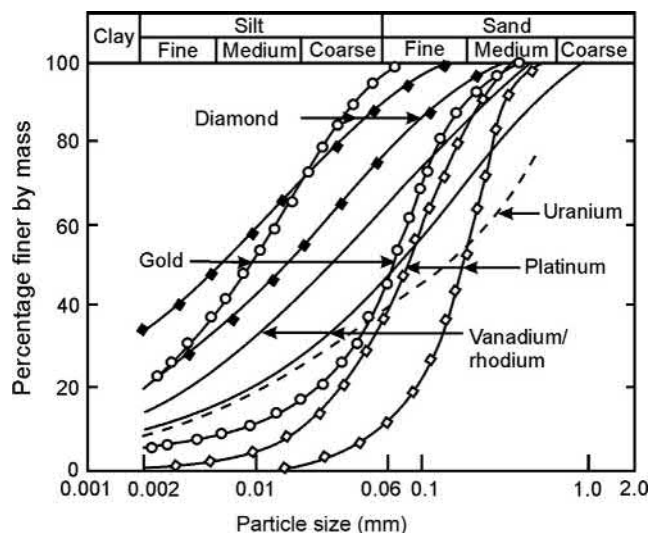
without compaction, or is used to progressively backfill opencast or strip-mining voids.

Fig. 6.2 shows typical particle size analyses for a range of tailings from various sources. In the diagram, the horizontal axis represents the particle size in millimeters and the vertical axis represents the proportion of material finer than a specific size. For example, for the vanadium tailings, 63% is finer than 0.06 mm, that is, the tailings contain 63% of silt and clay-sized particles.

In addition to its physical characteristics, mine waste and especially tailings may have characteristics or contain substances that may be prejudicial to the health of those living near the waste storage or the local natural environment. Examples of these are:

- combustible substances, usually carbon;
- free asbestos fiber (See [Discussion Box 6.1](#));
- metallic sulfides, sulfuric acid, and metal sulfates;
- radon gas; and
- soluble salts of heavy metals, for example arsenic, cadmium, copper, lead, or nickel.

FIG. 6.2 Particle size analyses for typical tailings from mineral extraction of various ores (e.g., Vanadium tailings contain 63% of particles finer than 0.06 mm).



DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS

Mining rock for ore and manufacturing of mined products from the ore emit considerable amounts of particulate matter at every stage of the operation. These particulates may include fine mineral dusts of a size to cause damage to the lungs. Depending on the type of rock, mineral fibers can also be released, notably asbestos. The threshold values for such dusts have been set quite low to prevent disabling diseases for the worker, including lung cancer, mesothelioma, pleural diseases, asbestosis, and silicosis.

After extraction, depending on the rock and the ore, downstream life cycle stages may involve crushing and grinding, pelletizing, and separating by magnets or sieving. Such postextraction processes can be enclosed and controlled to prevent the emission of particles. In many cases, the recovered particles can be returned to the process, that is, reused in an earlier stage in the product life cycle [6].

To make the math easier, such as when calculating aerodynamic diameter or Stokes diameter, airborne particles are often considered to be spheres, which may be true, for example, those found in

metal refining emissions [6–8]. In the real world, particles come in myriad shapes, including angular, for example, soil particles. One of the most troublesome morphologies is elongated particles, which are differentiated from other particulates as “fibers.” Such elongation is expressed as a particle’s aspect ratio, that is, the ratio of the length to width. Fibers generally have aspect ratios $>3:1$; often much greater. For example, the lungs of mice exposed to a complex mixture of fiber sizes and nonfibrous material known as the “Libby 6 mix” from the Montana vermiculite mining area had a mean aspect ratio of 16 [9].

Recently, the scientific community has differentiated elongate mineral particles (EMPs) as an important pollutant class. Asbestos is a naturally occurring EMP, which has been mined and used for many industrial purposes.

The term, asbestos, is a regulatory term. In the United States, for example, regulators limit asbestos to six fibrous hydrated silicate minerals [10] (See Table 6.1), even though about 400 minerals have fibrous morphologies [11]. Exposure to

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS *(cont'd)*

TABLE 6.1 Asbestos Minerals in the United States

Name Used by Federal Regulatory Agencies	Mineral Name	Mineral Group	Chemical Formula
Chrysotile	Chrysotile	Serpentine	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$
Tremolite asbestos	Tremolite	Amphibole	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Actinolite asbestos	Actinolite	Amphibole	$\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Anthophyllite asbestos	Anthophyllite	Amphibole	$\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$
Crocidolite	Riebeckite	Amphibole	$\text{Na}_2\text{Fe}_3^{2+}, \text{Fe}_2^{3+}\text{Si}_8\text{O}_{22}(\text{OH})_2$
Amosite	Cummingtonite-Grunerite	Amphibole	$(\text{Mg}, \text{Fe}^{2+})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$

airborne asbestos fibers is known to produce debilitating health effects in humans. "Total EMP" includes any mineral particle with a minimum aspect ratio of at least 3:1, but which is also small enough to penetrate the airway, that is, inhalable, thoracic, or respirable size [12]. An amphibole EMP is a subset comprised of double chain silicate minerals, that is, crocidolite, amosite, anthophyllite, tremolite, and actinolite, which can be asbestiform or nonasbestiform [13]. An asbestiform EMP is usually narrower, longer, and more flexible than a nonasbestiform EMP [14].

As indicated in Table 6.2 the chemical composition of particulate matter emitted by mining activities varies by the mineralogy of rock strata in an area, but also by distance from the mining site. In this case, samples taken in and near a taconite mine show that, not surprisingly, the ore contains the highest amount of iron, which drops with distance from the mine. The clay content shows the opposite trend, as soil mixes with the particulates from the ore and tailing piles. What the table does not show is the number and types of EMPs.

Mining and ore processing activities produce asbestos, a group of highly fibrous minerals with

separable, long, and thin fibers. Cases of mesothelioma have also been seen in individuals without occupational asbestos exposure who live close to asbestos mines [15]. Human exposure to concentrations much higher than 10^{-4} fibers mL^{-1} is suspected of causing health effects. Asbestos fibers are very persistent and resist chemical degradation (i.e., they are inert under most environmental conditions) so their vapor pressure is nearly zero meaning they do not evaporate, not do they dissolve in water. However, the most commonly encountered asbestos, chrysotile, may degrade slowly in acidic environments. In addition, previously mined areas can be problematic since segments of fibers of even for the more resistant forms will enter the air and water as asbestos-containing rocks and minerals weather naturally or are physically altered during mining operations [16].

Waste managers should also be aware that products containing asbestos enter the waste stream as solid wastes, from construction, renovation, and repair. Indeed, among the most important exposures is when manufactured products, like pipe wrapping and fire-resistant materials, wear down. Small diameter asbestos

Continued

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS *(cont'd)*

TABLE 6.2 Bulk Sample Microscopic Analysis of Particulate Matter Near a Taconite Ore Processing Facility in Minnesota

Component	Ore Percent Volume	Tailings Basin	Roadside in Nearby Neighborhood	Window Seal in Nearby Neighborhood
Mineral—total	100	100	100	97
Quartz—feldspar	30	57	52	48
Limestone	<1	<1	<1	<1
Clay—humus	2	8	10	15
Magnetic iron	<1	2	2	2
Iron oxide	43	12	16	15
Other	25	21	20	17
Biological—total	0	0	0	0
Insect parts	<1	<1	<1	<1
Plant material	<1	<1	<1	<1
Pollen—spores	<1	<1	<1	<1
Starch grains	<1	<1	<1	<1
Other				
Combustion—total	1	1	0	1
Ash—cinder	1	1	<1	1
Coal—coke—oil	<1	<1	<1	<1
Cenospheres	<1	<1	<1	<1
Fine carbonaceous	<1	<1	<1	<1
Other				
Miscellaneous—total	0	2	0	2
Tire fragments	<1	<1	<1	<1
Wood fibers	<1	<1	<1	<1
Paper fibers	<1	<1	<1	<1
Concrete	<1	<1	<1	<1
Asphalt	<1	<1	<1	<1
Metal fume	<1	<1	<1	<1
Paint	<1	2	<1	2
Other	<1	<1	<1	<1

Data from Minnesota Pollution Control Agency, 2012.

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (cont'd)

fibers may remain suspended in the air for a long time and be transported advectively by wind or water before sedimentation. Like particles, heavier fibers settle more quickly. Asbestos fibers may break into shorter strands and, therefore, increased number of fibers, by mechanical processes, for example, grinding and pulverization.

Analytical Techniques

Because of its toxicity, effective monitoring techniques and analytical methods are needed to detect, quantify, and control asbestos in the environment. Whereas chemical composition is often the critical feature of particulate matter's health effects, the shape of EMPs is usually even more important. Therefore both morphological and chemical analysis of EMPs is need. These methods have been developed for a variety of purposes including support health risk assessments and controls.

Like all particulate matter, ELP's diameter determines the type and severity of disease that results from exposure. For example, asbestos exposure has been directly associated with three different diseases, mesothelioma, lung cancer, and asbestos, but these differ by the length and diameter of the fiber (See Fig. 6.3). The major concern with asbestos is when it is breathed in as a fiber. The size and shape of any aerosol, including a fiber, largely determines its toxicity. Fine particles (diameter $<2.5\mu\text{m}$) can infiltrate the lungs more deeply and deposit with greater efficiency than larger particles. Particulate matter (PM) is measured using instruments that draw air through filters that collect particles using size selection components to separate out the mass of each size fraction. These "dichotomous" samplers allow for separation of fine particles with aerodynamic diameters $<2.5\mu\text{m}$ ($\text{PM}_{2.5}$) from coarse particles with aerodynamic diameters $>2.5\mu\text{m}$, but $<10\mu\text{m}$ (PM_{10}) [16].

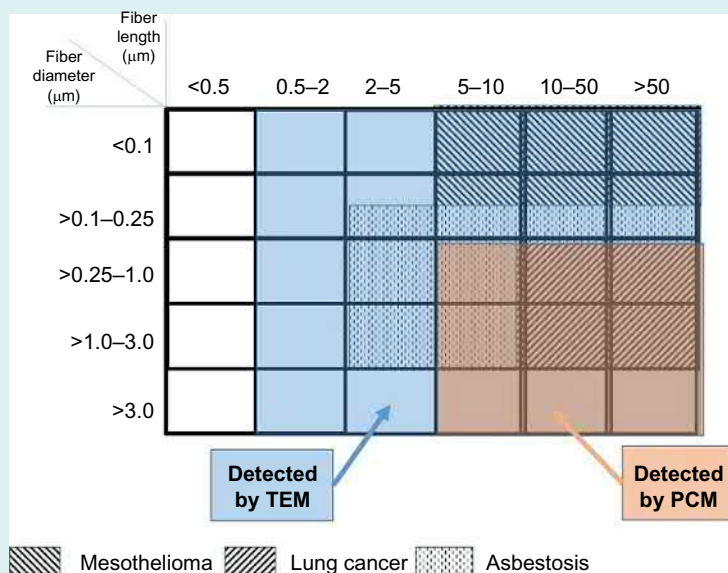


FIG. 6.3 Length and diameter ranges of asbestos fibers and associated diseases, along with the comparative detection ranges for transmission electron microscopy (TEM) and phase contrast microscopy (PCM). Drawing by D.A. Vallero; modified from P. Baron, *Measurement of fibers*, NIOSH Manual of Analytical Methods, 2003, pp. 143-166; adapted from K. Ashley, *NIOSH manual of analytical methods 5th edition and harmonization of occupational exposure monitoring*, Gefahrst. Reinhalt. Luft. 2015(1-2) (2015) 7.

Continued

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS *(cont'd)*

In addition to size and counts of fibers, optical and electronic microscopy can help to characterize morphological features of ELPs. These techniques include phase contrast microscopy (PCM), polarized light microscopy (PLM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The chemical constituents of ELPs can also be analyzed, for example, by X-ray diffraction spectrometry (XRD). Following are brief descriptions of these processes [17, 18].

Phase Contrast Microscopy

Airborne levels of asbestos in the workplace can be monitored using PCM. Air samples are collected on a 0.45–1.2 μm cellulose ester membrane filter. A portion of the filter is mounted on a microscope slide, cleared using an organic solvent and fibers are observed in a bright field at a magnification of 100 to 400 $\times$. PCM is reported to detect fibers as thin as 0.25 μm in thickness. PCM can detect fibrous materials but cannot directly distinguish asbestos fibers from other fibrous materials. PCM is typically used in workplace environments where the fiber type is known. Quantitatively, PCM methods report fibers per cubic centimeter of air sampled (f cm^{-3}). Normally fibers longer than 5 μm in length and having an aspect ratio (length to width) of 3:1 or greater are counted. Some protocols use an aspect ratio of 5:1 and count fibers with diameters $<3 \mu\text{m}$. It should be noted that current risk models are based on fibers with a 3:1 aspect ratio and data from methods employing a 5:1 aspect ratio cannot be used by such models.

Polarized Light Microscopy

Asbestos and other fibers, and minerals in bulk samples can be measured using PLM, in which the bulk material is examined by stereomicroscopy at a magnification between 10 and 60 $\times$

and subsamples of the various phases in the material are taken and mounted on a microscope slide in various refractive index liquids. Fibers are examined by PLM at magnifications between 100 and 500 $\times$ and identified by their optical properties including morphology (characteristic shape), color, refractive indices, birefringence, extinction angle, and sign of elongation. Characteristic dispersion staining colors are also commonly used to identify mineral type.

PLM methods typically report fibers by percent area or percent weight. The percentage may be estimated by visual estimation, comparison with charts showing various area percentages or with gravimetrically prepared standards, or by a point counting procedure. Although point counting is a systematic means of determining the relative amounts of materials in a mixture, it is not a reliable means of determining mass since one point may represent a single thin fiber or a large mineral “boulder.” Quantitative PLM results using these techniques are usually referred to as “semiquantitative” because they do not measure quantity directly. Some PLM procedures call for calculating the volume of each fiber, summing these volumes, and multiplying by the density of the fiber detected to calculate a total mass. If a sample has been processed to eliminate the matrix, the quantity of asbestos may be estimated by the loss in weight. It is difficult for the analyst to effectively convert the number of fibers observed by microscopy into a mass percent result.

X-Ray Diffraction Spectrometry

XRD is used to identify and to quantify mineral phases of EMPs, including asbestos. The method directs an X-ray beam to the sample, producing a diffraction pattern characteristic of the mineral phase. The observed pattern is then compared to standard patterns produced by known minerals by means of reference files or through

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS *(cont'd)*

computer analysis. XRD cannot distinguish between asbestiform and nonasbestiform materials of the same mineral phase. All identification of possible asbestos minerals by XRD must be confirmed by observing the fibers either by PLM, SEM, or TEM.

Scanning Electron Microscopy

Typically, samples are collected on either cellulose ester or polycarbonate membrane filters and prepared for analysis. Filters or bulk materials are carbon coated or gold coated and mounted on a sample “stub.” An electron beam is directed at the sample and emissions are measured by a detector at an angle to the electron beam. An image of the surface features on the filter is generated and fibers may be observed and counted (See Fig. 6.4). SEM magnifications may range from 2000 to 20,000 $\times$ and higher. SEM is more focused, so it can detect fibers that are much thinner than those detected by optical microscopy. Newer SEM devices can detect fibers narrower than the 0.25 μm limit for the PCM method. An energy dispersive spectrometer (EDS) unit used in conjunction with the SEM may also detect the chemical composition of the fiber observed allowing distinction between fibers showing a chemistry consistent with asbestos and other minerals. Fibers measured by SEM are typically reported in fibers per cubic centimeter. Fibers in bulk materials measured by SEM are typically reported as a percentage of the total sample with the percentage determination being made by visual estimation, comparison with standards of known composition, or gravimetry.

Transmission Electron Microscopy

Samples collected on membrane filters or bulk samples transferred to membrane filters are carbon coated and a thin carbon layer including

the fibers is transferred to a grid for TEM analysis. An electron beam is transmitted through the sample and an image of the material on the grid is projected onto a screen. TEMs provided magnifications from about 5000 to 20,000 $\times$ or more and fibers with diameters of about 0.01 μm can be detected. Like the SEM, an EDS unit can provide the chemical composition of the fiber. Selected area electron diffraction (SAED) directs an electron beam to the fiber to generate an electron diffraction pattern that indicates the crystal structure of the material. Regulatory agencies usually consider the TEM to be the most definitive technique for detecting and identifying asbestos materials.

TEM typically reports in fibers per cubic centimeter. Fibers in bulk materials measured by TEM are typically reported as a percentage of the total sample with the percentage determination being made by visual estimation, comparison with standards of known composition, or gravimetry. Some methods size each fiber, calculate the volume, and use the density of the fiber to determine a mass. Masses for all fibers are then summed and used to determine mass or percent mass. Counting protocols for fibers by TEM are similar to those by SEM [18].

The optical microscopy techniques typically use magnifications of about 400–500 $\times$ while the electron microscopy may use magnifications of 2000–20,000 $\times$. The higher magnification of the electron microscopy techniques allows for the detection of thinner fibers than those detected by the optical techniques [14, 15, 17, 18]. However, since the amount of sample observed at higher magnification is usually much less than the amount observed at lower magnification, quantitative analysis by electron microscopy may be impractical for some applications due to the small amount of sample analyzed.

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DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS (cont'd)

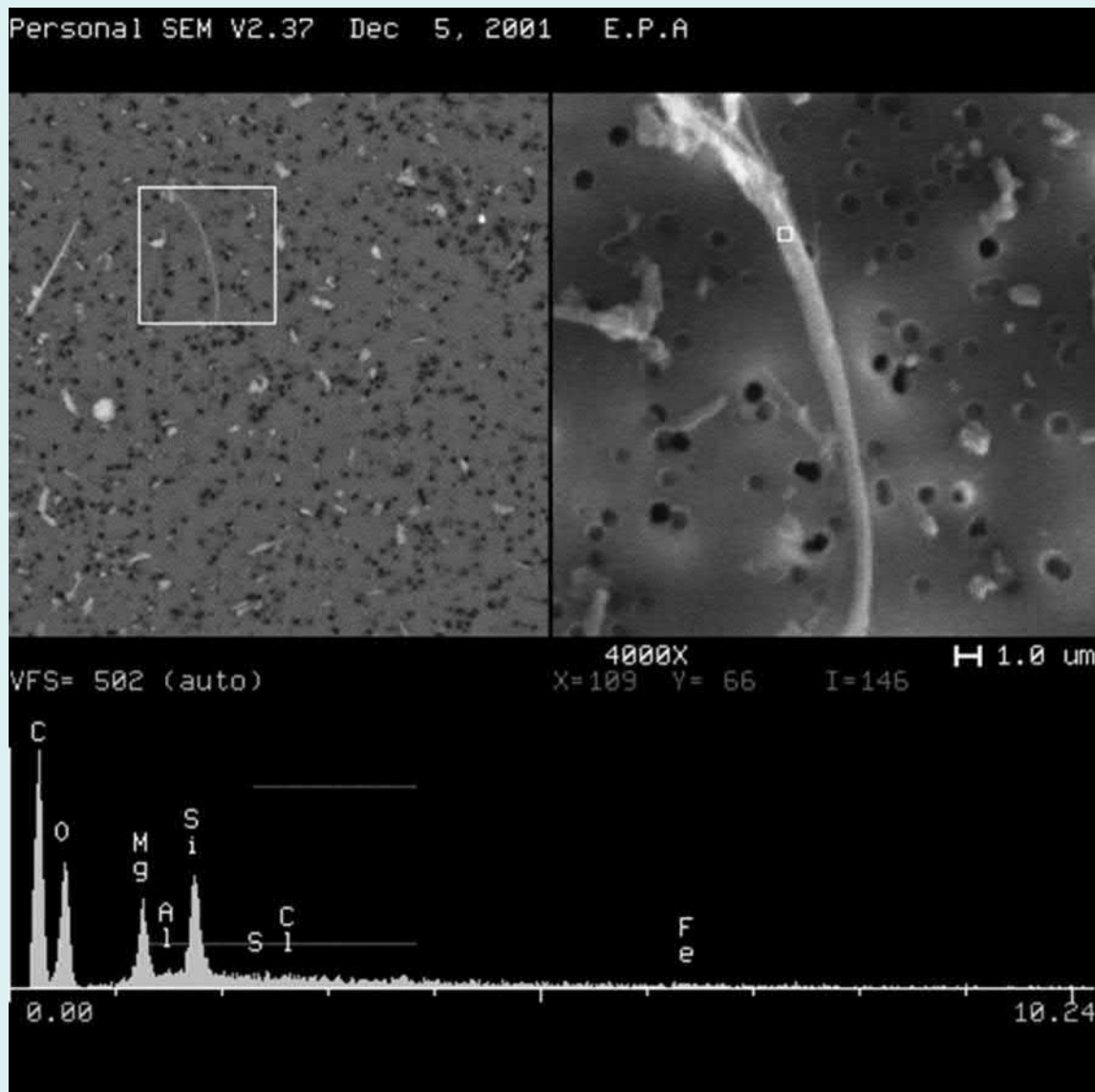


FIG. 6.4 Scanning electron micrograph of fibers in dust collected near the World Trade Center, Manhattan, NY in September 2001. Acquired using an Aspex Instruments, Ltd. Scanning electron microscope. The bottom of the micrograph represents the elemental composition of the highlighted 15 μm long fiber by energy dispersive spectroscopy (EDS). This composition (i.e., O, Si, Al, and Mg) and the morphology of the fibers indicate they are probably asbestos. The EDS carbon peak results from the dust being scanned on a polycarbonate filter. *Courtesy of U.S. Environmental Protection Agency, 2004. Photo courtesy of T. Conner, used with permission.*

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS *(cont'd)*

Exposure

Exposure to EMPs, like other particulate matter can be occupational or environmental. Occupational exposures during mining differ from those during ore processing, handling tailings, and other postmining activities. For example, surface mining can cover many hectares, whereas processing often takes place in much smaller, confined areas. Thus miner exposure may be similar in type to environmental exposures, that is, from air transport, but at much higher concentrations. However, since occupational regulations require personal protective equipment, the

exposures may be lower than those from environmental exposures in nearby communities (See Fig. 6.5). Environmental exposures often result from EMPs that are blown off or ore and tailing piles, fugitive emissions from not only disturbance of rock formations, for example, blasting, but also from unpaved roads from the mine to processing facilities, and outdoor storage piles.

Naturally Occurring Asbestos

Mining, whether for asbestos or for other materials found in asbestos-laden strata is not

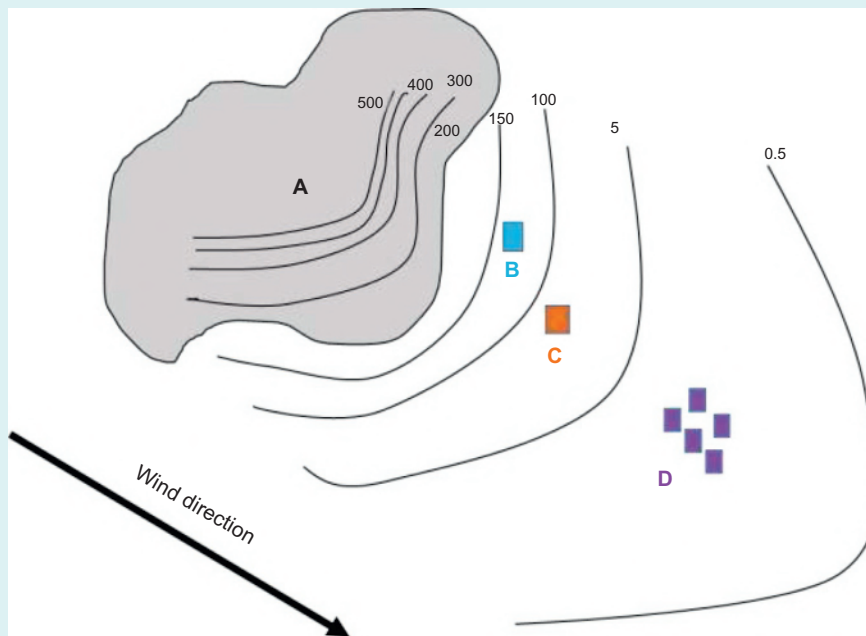


FIG. 6.5 Occupational versus environmental exposure (isopleths in mgL^{-1}). In this hypothetical illustration, the miner (A) working in the mine (gray area) with about 500mgL^{-1} is using personal protective equipment, so that even though the particulate matter (PM) concentration is 500mgL^{-1} , the personal exposure of the miner is only $150\mu\text{gL}^{-1}$ using a 99.97% efficient respirator. A person living near the mine may be breathing a thousand times higher concentrations of PM in his yard. Even with distance, the environmental exposures are higher than those of the protected worker, with (C and D) being exposed to >5 and 0.5mgL^{-1} , respectively. Drawing by D.A. Vallero.

Continued

DISCUSSION BOX 6.1 MINING AND ELONGATED MINERAL FIBERS *(cont'd)*

only problematic in active mines, but in the uses of the land that follows. Time series and other epidemiological studies have shown that new cases of asbestos-related diseases can arise after mining has ceased [19].

Naturally occurring asbestos (NOA) is comprised of asbestos and asbestiform minerals that are found in place in their natural state, such as in bedrock or soils [19]. The main concern arises when human activities lead to increased exposure to NOA, such as when construction or natural erosion disturbs the rock and soil. In mined areas, the disturbance has already occurred, so simply using the road, path, school yard, and so on, may lead to exposures to ELPs.

Areas of NOA can be relatively confined to several km². Thus NOA is indeed a concern for any waste manager for several reasons. Siting any waste facility, such as a landfill or combustor, should determine the presence of NOA and, if present, what actions to take and to avoid. A municipality may receive wastes from areas with disturbed or underlying NOA, so these materials may find their way to waste handlers and disposal sites. In addition, waste managers and engineers may be consulted or be members of advisory groups on plans for areas of NOA. As such, the advice and consultation must hold paramount the safety, health, and welfare of the public [20–22].



FIG. 6.6 A burning dump of coal waste.

The first and third examples are particular problems with coal wastes, which often catch fire as a result of spontaneous heating caused by oxidation of metallic sulfides contained in the coal. Oxidation of sulfides also results in

the production of seepage containing sulfuric acid and soluble metal salts such as iron and magnesium sulfates. Fig. 6.6 shows a burning dump of coal waste. Once on fire, a large dump like this, often containing several million tons of

combustible material, is a major source of air pollution and very difficult, dangerous, and costly to extinguish.

3 STORAGE OF FINE-GRAINED WASTES

Fine-grained wastes (tailings) containing a high proportion of silt-sized particles are the most difficult wastes to store. Some fine-grained wastes can be “dry-dumped” or “stacked” either by truck or belt conveyor, although they must always contain some water to prevent dust pollution arising during transport and deposition. However, economics dictate that most of the tailings be transported hydraulically either as a slurry or as a “thickened tailings” or “paste” and be deposited or “beached” into hydraulic fill tailings storages where the tailings flow under their own weight, settle, and consolidate to form fine-grained silty deposits. Alternative methods of deposition are to discharge a thickened tailings slurry from a single, or a series of, point discharges around each of which the tailings form a flat-sloping conical deposit; or to transport a

tailings paste by conveyor belt and discharge it from a preconstructed earthen ramp to form a wedge-shaped deposit by viscous flow.

Fig. 6.7 shows a hydraulic fill storage of fine tailings formed by “beaching,” that is, by depositing a slurry of tailings around the outer perimeter of the tailings storage and allowing it to run down a “beach” toward the pool of water formed in the arms of the Y-shaped causeway or pool training wall. The darker (wet) surfaces show where slurry has recently been deposited. Water that collects in the pool is decanted through a vertical decant shaft that is visible at the center of the Y. The decant shaft leads to a subhorizontal outfall pipe or conduit that leads the decanted water to a return water reservoir, before being returned to the mineral extraction plant.

4 WATER BALANCES FOR MINE WASTE STORAGE

A water balance is a statement that sets out how much water enters, leaves, and is stored in tailings storage. Water enters as a component of the waste slurry and as rain, and it can be



FIG. 6.7 A typical hydraulic fill tailings storage constructed by “beaching” toward a decant shaft.

recovered as water decanted from the pool and collected from the drains around the storage. A large proportion of the water remains in the void spaces between the solid waste particles and cannot be recovered, and a proportion is lost by evaporation from the outer surface of the storage and by seepage into the ground strata under the storage. Water balances are used to estimate and control the quantities of water involved in the waste storage process and for environmental control by checking on the quantities of water lost in seepage to the natural ground water.

Every hydraulic fill waste storage has a water or seepage surface in it, called the phreatic surface, where the pressure of the water is the same as the atmospheric pressure. Below the phreatic surface, the water pressure is greater than atmospheric pressure and acts to destabilize the outer containing slopes of the storage. Above the phreatic surface, the pressure of the water is less than atmospheric pressure and helps to stabilize the slopes.

Fig. 6.8 shows the components of the water balance for a hydraulic fill tailings storage, including the phreatic surface and the drains designed to release water from the tailings and

enable it to be returned to the mineral extraction plant, via the return water reservoir.

When a mine waste storage ceases operation, the pool is drained and thereafter remains dry except for rainfall that runs off from the surface. The phreatic surface slowly subsides once the supply of slurry water ceases and the outer slopes of the storage become more stable. At this stage, the surface of the waste storage needs to be “rehabilitated” which means that the waste surface is protected from erosion by water and wind and is usually planted with indigenous vegetation to enable it to blend, as much as possible, into the natural landscape.

5 SAFETY OF MINE WASTE STORAGE STRUCTURES DURING THEIR OPERATIONAL LIFETIME

Mine waste storages are very large structures, easily visible from space, that have very long operating lives (often >50 years) and often were not properly planned in the first place or carefully operated. They are under construction for the whole of their operating lives and are

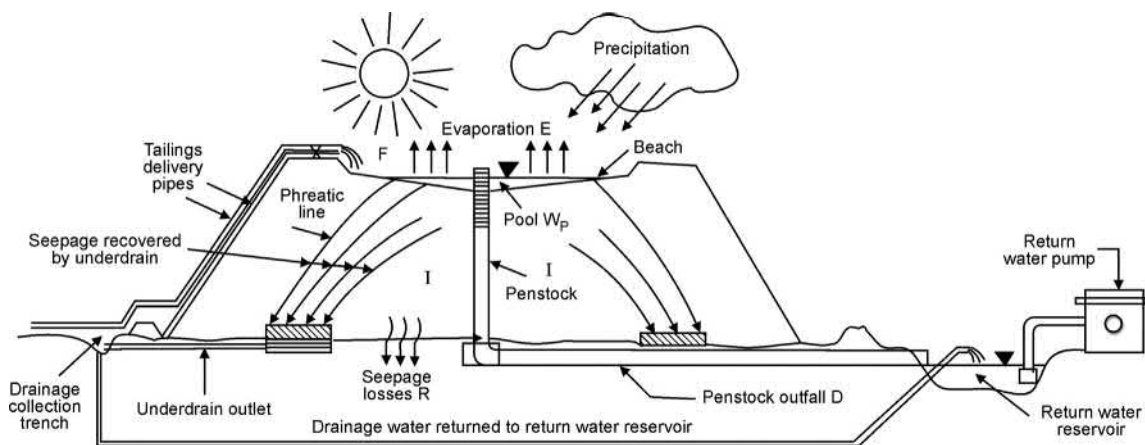


FIG. 6.8 Diagrammatic representation of components of a water balance for a beached unthickened tailings storage.

operated by a succession of people, not all of whom are dedicated to carrying out their assigned tasks to the best of their abilities, not all of whom are properly trained, and not all of whom understand why they must undertake certain tasks and what the consequences of negligence may be. Not all of the workers can recognize that a dangerous situation may be developing, and not all of them know the correct course of action to be taken in an emergency. The foregoing statement is not flattering, but it is a reality. Adding to the unknown dangers are natural hazards; severe rain storms; earthquakes; undetected adverse geological or ground water conditions; human errors such as well-intentioned, but faulty design, theft, or lack of maintenance of vital components; warning systems that fail at the crucial time; and finally, so-called Acts of God.

Failures of tailings and coarse waste storages can take many forms, the most dangerous and destructive of which are those in which the waste loses strength, becomes mobile, and flows as a viscous liquid in which the supporting fluid

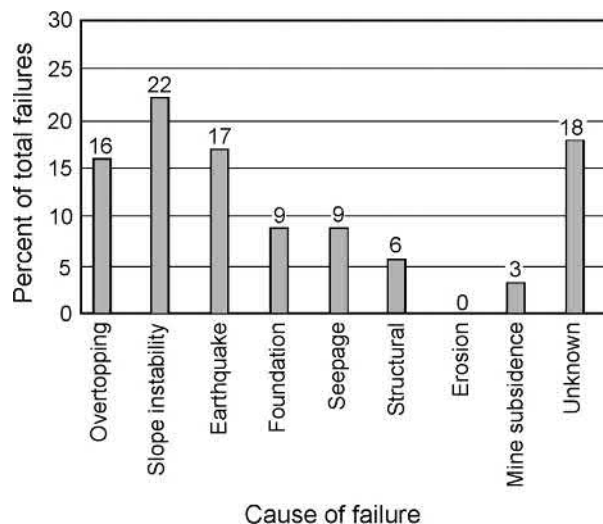
can either be air in deposits of dry waste, but more commonly, water. Nineteen major flow failures of tailings storages occurred between 1928 and 2000, which together caused at least 1080 deaths of which 1065 occurred between 1965 and 1996, an average of >34 deaths per year. Deaths from failures of other forms of waste storage do not lag behind. Deaths caused by only three failures of municipal solid waste dumps between 1993 and 2005 alone, totaled 464, an average of >38 deaths per year [23]. However, to keep these numbers in perspective, it must be remembered that they are miniscule in comparison with the yearly death toll on the roads of the world and with other preventable causes of death, such as HIV-AIDS.

It is also interesting to note that many of the 19 failures occurred in small waste storages at operations that were being run on a “shoe-string,” or at mines threatened by closure. The failures at Stava, in 1985, which killed 268 people and Star Diamonds (see Fig. 6.9) were of this type. Also, by no means all mine waste



FIG. 6.9 Aftermath of the collapse of a tailings storage at a diamond mine into shallow underground workings. The level of the tailings before the collapse can be seen as a level surface in the background. The small pump barge is located over the site of the collapse.

FIG. 6.10 Analysis of causes of 185 tailings dam failures.



“incidents or accidents” are reported in the widely read or viewed news media nor do all lead to disasters.

Fig. 6.10 summarizes the causes of 185 failures of hydraulic fill tailings storages, collected by the United States Commission on Large Dams [24]. Explanations of the listed causes of failure are given as follows.

5.1 Overtopping

Overtopping occurs when the pool of water around the decant shaft (see Fig. 6.7) either grows so large that it reaches and overtops the impoundment wall, or the pool moves away from the decant shaft due to uneven distribution of the tailings around the pool. If this happens, the water cannot be decanted and if the problem is not noticed and corrected, the pool may overtop the outer wall. The usual cause of overtopping is holding too much water on the top of the storage, resulting in an insufficient height margin or freeboard to contain water suddenly deposited by a large rain storm. Overtopping usually results in the eroding of a breach in the storage outer wall, possibly causing the contents of the storage to liquefy and

flow out of the breach. (It is not quite correct to rule out erosion as a cause of failure, as in Fig. 6.10. Erosion may not be a primary cause of failure, but it often forms part of the process of failure.)

5.2 Slope Instability

Slope instability occurs when the strength of the material forming the outer wall of the storage is insufficient to carry the weight of the wall, with the result that a segment of the wall slides out on a failure surface that is often cylindrical in shape. Fig. 6.11 shows a typical slope instability failure or slide in the outer wall of a tailings storage. (The moment of the weight W about the center of rotation O became too large for the moment of the shear forces S about O to resist.) In this real example, the rotational movement on the failure surface was relatively small and the freeboard of the storage surface was reduced by height AA^1 of just $>2\text{m}$. However, because tailings storages are sometimes operated with freeboards as low as 1.0m , even a loss of freeboard of 2m could have resulted in overtopping, followed by erosion and a flood of escaping liquefied tailings.

2. WASTE STREAMS (AND THEIR TREATMENT)



FIG. 6.12 Failures of a gold tailings storage at Saaiplaas mine that was being built at an excessive rate of rise. (Two failures are visible, side by side in the center of the photograph, and one in the center-right.)

nobody was injured and damage was confined to the mine property.

5.6 Structural Failure

Structural failure is a poorly defined term, but might include the result of damage from burst tailings delivery pipes, resulting in the cutting of an erosion gully, or the collapse of the decant control structure, either the outlet shaft or the outlet pipe, also resulting in erosion damage.

5.7 Mine Subsidence

Failure caused by mine subsidence usually occurs when tailings are stored on surface over shallow mine workings, and the strata between the underground workings and the ground surface collapse, allowing tailings to flood into the underground workings. Fig. 6.9 shows the result of one such occurrence in which four miners were drowned underground. In a similar accident in Zambia in 1970, 89 miners were drowned underground.

6 DECOMMISSIONING, CLOSING AND REHABILITATING TAILINGS, AND OTHER MINE WASTE STORAGE

The decommissioning and closure processes consist of removing all the installations associated with operating the storage, such as tailings delivery pipes, conveyors, and so on. A permanent surface drainage system is installed, sealing the decant system and replacing it with a permanent spillway, and the surface of the storage is reshaped so that surplus surface water can enter the surface drainage system and either be held on the top surface of the deposit, to evaporate, or be conducted to natural ground level without causing any erosion or flooding. At natural ground level, the surplus surface drainage should be purified, if necessary, and channeled into a natural water course.

The biggest problem in rehabilitating the surface of a closed waste storage is to permanently protect the surface from water and wind erosion, thus maintaining a stable surface in which

vegetation can be established. Cleaning up any waste site, especially the large ones associated with mining, involves risk trade-offs, for example, whether the remediation itself will increase the amount of waste constituents like heavy metals temporarily in order to lower future risks. These releases will be worsened if engineering and other mistakes are made (See [Discussion Box 6.2](#)).

It is becoming more and more common for regulatory agencies to require that the rehabilitation of a tailings dam or other waste deposit be designed to be maintenance free for 500–1000 years. This seems quite unrealistic

when one thinks of the changes only 100 years can cause to a landscape (e.g., the areas now occupied by the cities, freeways, and waste deposits of many cities in the “new world” were untouched countryside just over a century ago). However, very ancient man-made earth mounds exist in many parts of the world with slopes that have been subject to 1000 or more years of erosion and still exist in good condition. [Fig. 6.14](#) shows the profiles of several ancient man-made monumental mounds in China [28]. All these are accurately dated and are from 700 to >2000 years old. The mounds around Xi’an are all constructed of fine sandy silts from

DISCUSSION BOX 6.2 GOLD KING MINE

Some 23,000 abandoned mines exist in Colorado. Recently, one of these, the Gold King Mine near Silverton, Colorado became notorious as a source of heavy metals and other contaminants. The mine exists in the Upper Animas Watershed in the southwestern part of the state. Mining altered the hydrology and hydrogeology, which changed the speed and amount of water reaching streams.

The Rocky Mountains contain pyrite (iron sulfide) that reacts with oxygen to form sulfuric acid, which increases the rate and amount of metals that can be dissolved in water. Mines in this area exacerbate these physical and chemical processes, allowed the acidic, metal-laden surface water and groundwater to enter the mine’s horizontal access and drainage conveyances known as adits and vertical shafts (See [Fig. 6.13](#)). Mining ended at Gold 1991 and the mining company plugged, that is, bulkheaded, the mine and to remediate other nearby mines nearby, and to decrease the amount of metal-laden waters transported away from the mine. Given the extent and intensity of the disturbance, however, the

leaching and transport of contaminants continue after mining ends [25].

The U.S. Environmental Protection Agency (EPA) conducts environmental investigations as part of its regulatory authority. On August 5, 2015, EPA was conducting an investigation of the Gold King Mine to assess the ongoing water releases from the mine, to treat mine water, and to assess the feasibility of further mine remediation [26]. While excavating atop an abandoned adit, pressurized water started to leak above the mine tunnel, over a nine-hour period, releasing over 11 million liters of water that had been stored behind the collapsed material.

The contaminated water reached Cement Creek, a tributary of the Animas River and San Juan River, reaching Lake Powell. The water contains the metalloid, arsenic, and the metals aluminum, cadmium, copper, iron, lead, manganese, mercury, and zinc [27].

EPA has taken responsibility for the release and has been working with local communities, states, and tribes to address the harm.

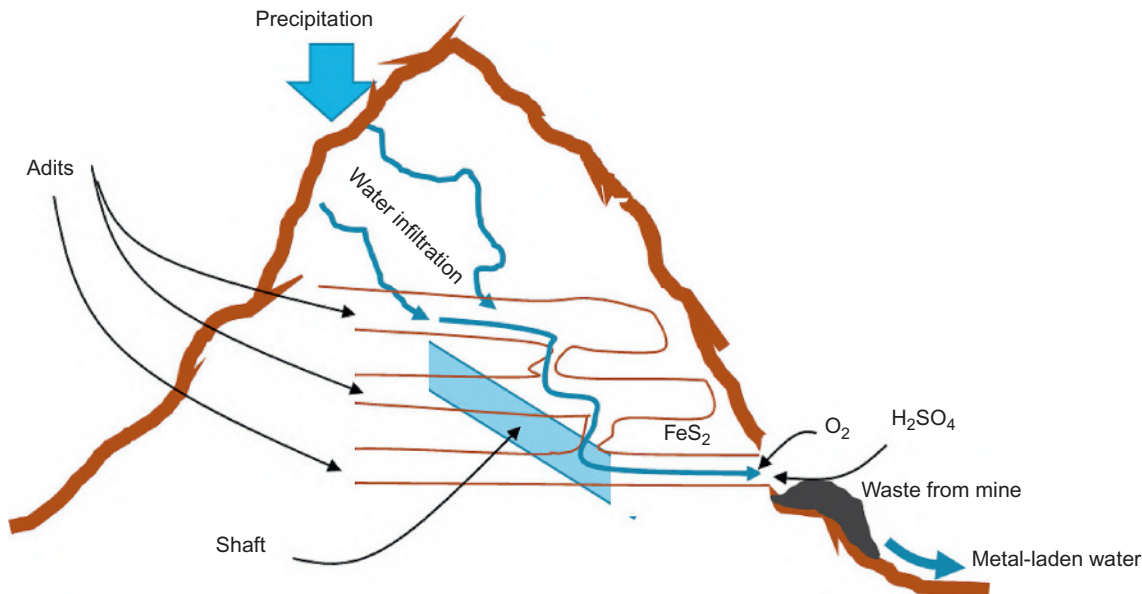


FIG. 6.13 Side view of mine workings into which water infiltrates, dissolves iron sulfide (pyrite) in the rock, and then reacts with atmospheric oxygen to form sulfuric acid. The lower pH increases the rate of metal dissolution, so that the acidic, metal-laden mine drainage that contaminates surface water and groundwater. Drawing by D.A. Vallero; modified from J.P. Thompson, *An Acid Mine Drainage Explainer, and a Curious Account of the Gold King Circa 1901*, 2015. Available from: <http://jonathanthompson.blogspot.com/2015/08/an-acid-mine-drainage-explainer-and.html> (Accessed 20 March 2018).

river alluvium and loess, which are intrinsically fairly erodible. The climate has distinct wet and dry seasons, rainfall is between 500 and 1000 mm year⁻¹, and there is an annual water deficit, that is, potential evaporation from the soil exceeds rainfall. The mound near Yinchuan is also of loess, but the area has a desert climate. It might have been expected that over a period of 1000 years, the slopes would all have eroded to similar and very flat slope angles. But this has not occurred. As shown in Fig. 6.14, the slopes vary from 16 to 28 degrees. Hence, one cannot conclude that if a slope has less than a certain limiting angle, it will not erode. The contrast between the mounds near Xi'an and those near Yinchuan shows, however, that climate plays a role in determining an erosion-resistant slope. Observations and measurements of the erosion of the slopes of gold tailings dams in South Africa [29] have shown that an "erosion rate

surface" exists in a (slope angle-slope length-erosion loss) space. This surface, illustrated in Fig. 6.15, shows that erosion rates increase with slope length but are low both at very flat and very steep slope angles. The "belly" of the erosion rate "sail" at intermediate slope angles represents the range of slope angles often used for tailings dams (25–35 degrees), which thus usually have the worst possible slope angles for erosion losses.

The larger the surface strength of a slope, the lower is the rate of erosion. Hence, the effect of a varying surface strength would be like the wind on a spinnaker sail; it would move the erosion rate surface inward (as the shear strength increases) or outward (as the shear strength reduces) relative to that of the erosion loss axis (or "mast"). Protecting the surface of a slope, by armoring it or covering it with vegetation, has a similar effect to increasing the surface

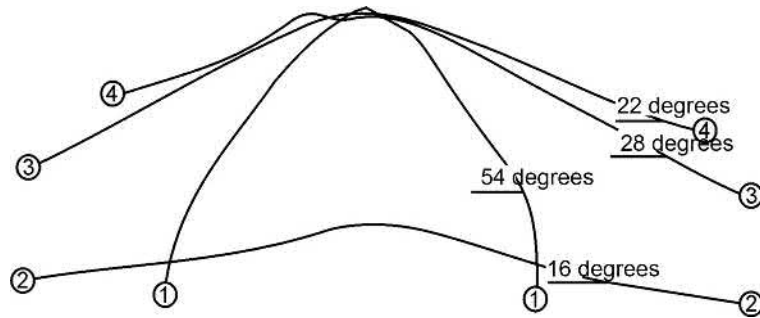


FIG. 6.14 Profiles of ancient earth mounds in China.

shear strength, and therefore moves the “sail” in, that is, back toward the “mast.”

Fig. 6.15 illustrates the following very important principles:

- *Slope angles* should be made as flat as possible. Around 10–15 degrees is practical and approaches the ideal angle.
- *Slope lengths* should likewise be limited. The maximum length should not exceed 25–30 m.

To achieve these two requirements, long slopes should be interrupted at height intervals of about 7–8 m by horizontal berms or steps

equipped with lined, erosion-proof surface drains designed to conduct the surface runoff from the slope above to ground level, without causing any erosion of the lower slope surfaces.

- *Very flat slopes and horizontal surfaces* (e.g., the flat top surface of a tailings storage) do not erode to any significant extent and hence do not require protection against erosion.

So far, the term “erosion” has not differentiated between wind erosion and water erosion. Both can be very significant. In wetter climates, water erosion predominates, and in drier climates, there is more wind erosion. In South Africa, for example, wind erosion accounts for two-thirds of total erosion and (perhaps surprisingly) in Iceland, wind erosion also predominates over water erosion.

Concerning *rates of erosion*, unprotected tailings slopes may erode at rates of up to $1000 \text{ t ha}^{-1} \text{ year}^{-1}$, whereas natural slopes usually erode at $50\text{--}100 \text{ t ha}^{-1} \text{ year}^{-1}$ or less. The aim of protecting tailings slopes should be such that their rate of erosion is reduced to $<100 \text{ t ha}^{-1} \text{ year}^{-1}$.

There is a controversy [30] as to whether the Qin mound (No. 2) was ever actually 116 m high, or whether this was the planned height, but the mound was only built to 52 m, its present height. If one calculates back 2200 years from the present height and plan dimensions of $330 \text{ m} \times 330 \text{ m}$, assuming a rate of erosion of $100 \text{ t ha}^{-1} \text{ year}^{-1}$

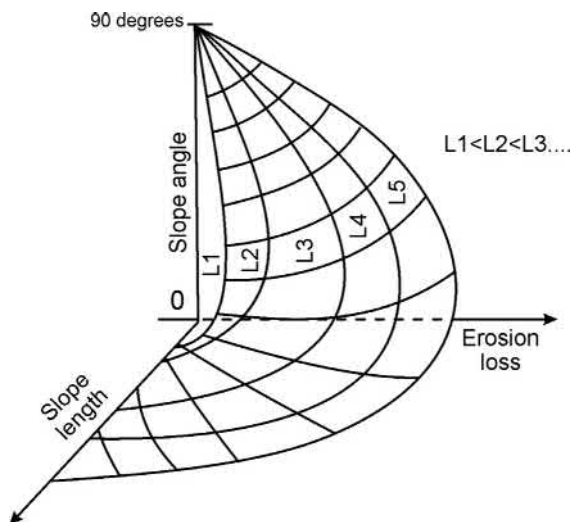


FIG. 6.15 Erosion rate surface.

(appropriate for the soil from which it is built) and maintaining the present average slope of 16 degrees, the calculated original height works out as 115 m. Hence, 115 m is a very likely original height. Because it was a memorial mound to the first emperor of a united China, it is likely that the mound has been maintained over the 2000 years since it was built. Nevertheless, its height has halved in that time. This illustrates the futility of legislating for a design period of even 100 years as a maintenance-free life. Closed tailings storages, like the Chinese mounds, cannot be made erosion free.

7 SUMMARY

Mining activities produce larger quantities of waste and have more adverse environmental impacts than waste from any other human activity. It is difficult to do more than briefly outline the subject of mine waste storage in a single chapter, and the reader is referred to a full-length book on the subject [23] for further details.

Mine waste can be divided into coarse-grained wastes that are usually stored in surface dumps, and fine-grained wastes, usually stored in hydraulic-fill structures. Both coarse and fine mine wastes could contain toxic substances, emit radioactive radon gas, or be combustible. Therefore mine waste storages need to be constructed and protected in such a way that their adverse effects on human health and the natural environment are minimized on a long-term, continuing basis. Fortunately, controls and statutory regulations for the storage of mine waste are being tightened in most countries, and at the same time, the engineering skills needed to construct and maintain storages safely and for long periods of time are also improving.

It is very important to realize that once a mine waste storage has been created, it constitutes a hazard that requires ongoing maintenance and care for millennia to come.

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Coal Waste Streams

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1 INTRODUCTION

One of the indicators of economic development is the extent to which a nation has centralized its utilities, especially electric power generation. Demand for electric power to heat and light homes, for appliances, communications, and other modern uses increases with increasing development [1]. Much of this demand is met by burning fossil fuels in large electric power generating stations, especially coal in its various forms, from lignite to anthracite (see Fig. 7.1).

Put simply, power plants convert one form of energy to another, before transporting that energy to the various users from manufacturers to households (see Fig. 7.2). Frequently, the first thing engineers and plant managers consider is how to remove as much of the pollutants before

emitting them into the air. This is a noble cause. An electric generating plant releases for both particulate (i.e., solids and liquids) and vapors. It would not be unusual in the United States, for example, for one plant to release gaseous emissions of 350,000 kg of oxides of sulfur per day and 185,000 kg of oxides of nitrogen per day. To meet emission limits set by governmental authorities, the plant manager must decide on actions that can include the acquisition of lower-ash or lower-sulfur coal. The manager may also modify the combustion process to lower the amount of particulate matter (fly ash) that is produced and emitted, but resulting in a greater amount of bottom ash that is generated that would have to be handled as solid waste (e.g., in an ash pit). Another option is to install more efficient air pollution control



FIG. 7.1 Kingston steam electric generating station on the Emory River, Tennessee. This 1.4-gigawatt coal-fired power plant is located next to Watts Bar Lake and is operated by the Tennessee Valley Authority. The plant is the site of a large fly ash spill in December 2008. *Courtesy of D.A. Vallero.*

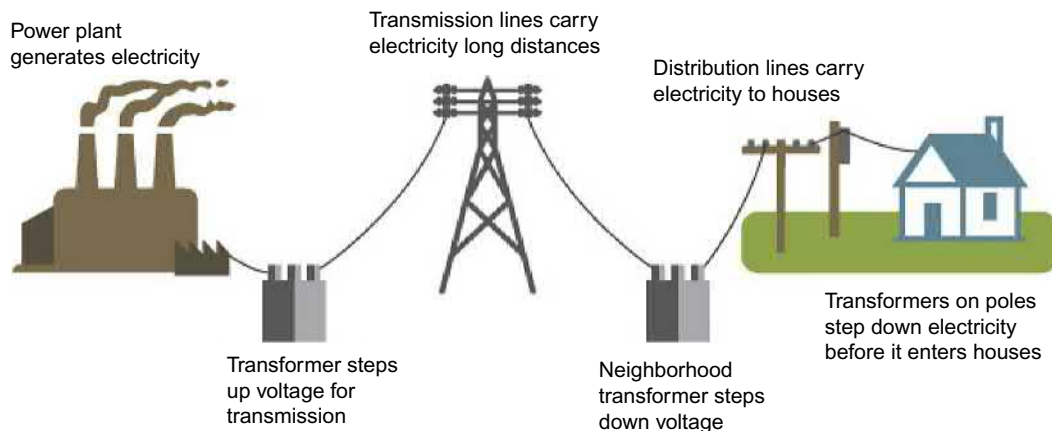


FIG. 7.2 US network of power plants and transformers linked by more than 450,000 miles of high-voltage transmission lines. Electric power is generated at power plants and then moved by transmission lines to substations. A local distribution system of lower voltage transmission lines moves power from substations to the user. *Courtesy of U.S. Department of Energy, Top 9 Things You Didn't Know About America's Power Grid, 2014, March 7, 2018. Available from: <https://www.energy.gov/articles/top-9-things-you-didnt-know-about-americas-power-grid>.*

equipment, but which again results in generation of more solid wastes, notably slurries from scrubbers needed to remove gas phase pollutants and fly ash from removal of particulate matter.

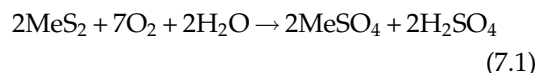
If a large steam generating plant, producing 2000MW, burns a million kilograms per hour of 4% ash coal, it must find ways to dispose of 40,000 kg of ash per hour [2]. Some will be removed from the furnaces by the ash-handling systems, but some will go up the stack with the flue gases. Thus if 50% of the ash enters the stack and the fly ash collection system is 99% efficient, 200 kg of ash per hour will be emitted to the atmosphere. Thus much of the pollution is simply transferred from the air to solid wastes. Obviously, the best solution is to decrease the demand for the electricity in the first place.

2 COAL STORAGE

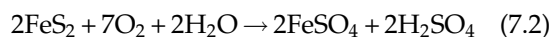
Waste managers and engineers must consider the electric generating station and its surroundings as a system if they are to avoid “cross-media transfer” [3], that is, the simple movement of solid, liquid, and vapor phase contaminants among the soil, groundwater, surface water, and the atmosphere (see Fig. 7.3). Contaminants move and transform physically and chemically within and between each environmental compartment or medium. For example, fugitive dust blowing off the coal pile at the power plant will become dissolved or suspended in water vapor (see Fig. 7.4).

Much of the precipitation onto a coal pile runs off the pile directly, with a fraction evaporating and percolating into the soil [4]. Drop-lets from the stack emission combine with vapors from the coal pile, ash impoundments, and other sources, then return to the earth’s surface as precipitation and again reach surface and groundwater [3–5]. During these flows between the atmosphere, water, and other compartments, the constituents react chemically and change valence, making them more or less

mobile and more or less toxic. For example, given the high sulfur content of most coals, the receiving waters become more acidic. The predominant and essential reaction when the metal (Me) in coal is exposed to oxidizing conditions is:



Iron, for example, would be:



Thus metal concentrations will increase with increasing sulfuric acid concentration, that is, decreasing pH in receiving waters. As a result, the species abundance, biological diversity of habitats, and other ecosystem features are diminished and degraded [6].

If an ecosystem is already stressed the adverse effects can be further exacerbated, for example, naturally from drought conditions or anthropogenically from waste effluents that lower dissolved oxygen concentrations in the receiving stream, lake or other surface water systems. Indeed, this exacerbation not only applies to metals that are intrinsically toxic, for example, lead, mercury, and cadmium, but to the iron that is usually present in coal and ash. Increased concentrations of ferric hydroxide, $\text{Fe}(\text{OH})_3$, for example, can change a benthic community’s diversity, with concomitantly increasing abundance of tubificid worms and chironomids downstream from mining sites and piles [6].

3 ASH HANDLING AND STORAGE

The need to handle the massive amount of residue from burning coal has been recognized even before there were power plants. Homes and small factories that were heated by coal furnaces had the challenge of dealing with the wastes that accumulated in stokers and other furnace mechanisms.

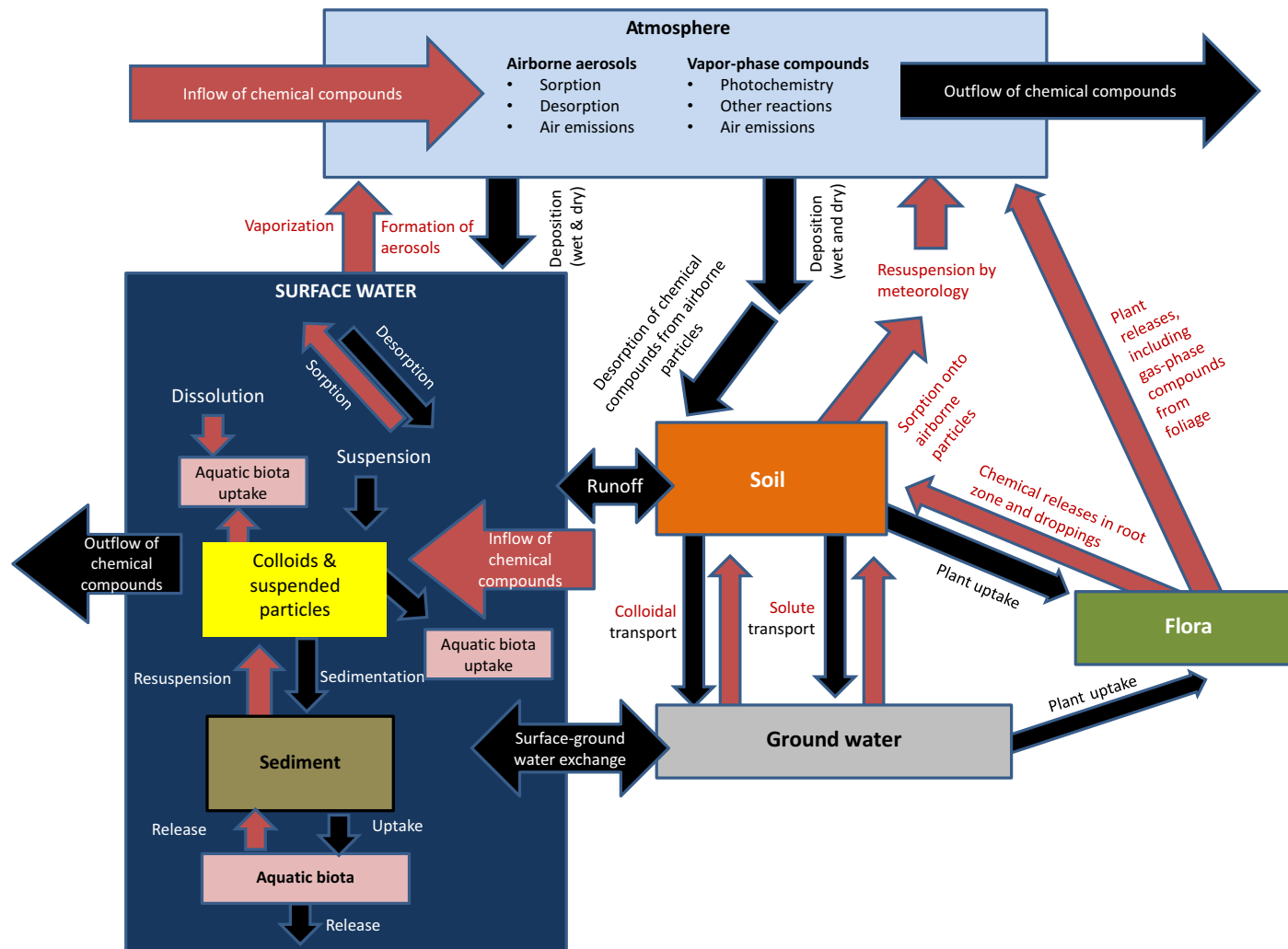


FIG. 7.3 Cross-media transfer of pollution, as represented by the flow of substances into and out of various environmental compartments. The *arrows* represent partitioning coefficients, and each *box* represents conditions that lead to reaction rates and kinetics that are unique to each chemical compound released from coal or ash substances. *Reproduced with permission from D. Vallero, Environmental Biotechnology: A Biosystems Approach, Elsevier Science, 2015.*



FIG. 7.4 Hanasaari Power Plant in Helsinki, Finland with large coal pile in foreground. Source: P. Sulonen. 2016. https://commons.wikimedia.org/wiki/File:Hanasaari_coal_heap.jpg. Wikimedia Commons. Accessed on December 4, 2018.

BOX: SON OF A COAL MINER

My father, James Vallero, Sr, my uncles and grandfather were coal miners in southern Illinois. I recall that one of the benefits of this was that we received cheap coal, which would be deposited in our front yard before the family would shovel it into an opening in our coal bin in the basement. Earlier the coal lumps were large, about 4 in. in diameter, but when we acquired a stoker, our coal lumps were smaller, about 1 in. diameter. With this smaller size, the ash characteristics became large “clinkers” (see Fig. 7.5), which my dad shoveled into the backyard. There was so much, he actually raised the elevation several feet.

It was much later that I came to appreciate that these clinkers were a type of bottom ash comprised of coke, grit, and other solids containing various toxic metals and metalloids. Indeed, any residue from coal combustion, for example, bottom and fly ash, will contain all of the parent

coal’s elements that have not volatilized into the atmosphere. In fact, the residues often concentrate these elements to be orders of magnitude higher than their concentrations in the unburned coal.

Coal mining has left an indelible mark on the Vallero family, both literally and figuratively. Literally, my father and others’ lungs were stained from breathing coal dust over the decade and were diagnosed with pneumoconiosis, “Black Lung.” My home town, Collinsville, Illinois, still bears the marks of the now defunct Lumaghi Coal Mine. Government funds have been spent to cover the large gob piles of slate and other impurities from the coal refining processes. Figuratively, my perception of the world has been colored by growing up in a town so beholden to coal mining. As an engineer and scientist, I know that risk-based decisions must certainly

Continued

BOX: SON OF A COAL MINER (cont'd)

be underpinned by sound physical and biological sciences, but must also consider the social aspects. In Collinsville, the miners and their families had to balance the risks with the benefits of having a job. I remember vividly that when the mine closed, for my father and Uncle Louie, who were still working at that time, it was a very

sad day. Throughout Collinsville, it was hard to find any miner or his family who was happy. But, from a risk assessment perspective, the end of exposure to coal dust, not to mention mine collapses, may well have added decades to my father and uncle's lives on earth.



FIG. 7.5 Clinker from residential coal furnace. Reproduced with permission from Old Ferguson West, *Buried Treasure*, 2018, March 6, 2018. Available from: <http://www.oldfergusonwestneighbors.com/Neighborhood/History/Treasure.aspx>.

Coal ash is of various types [7]. Fly ash is very fine, powdery material composed mostly of silica made from the burning of finely ground coal in a boiler. Bottom ash is a coarse, angular ash particle that is too large to be carried up into the smoke stacks so it forms in the bottom of the coal furnace. Boiler slag is molten bottom ash from cyclone or slag tap furnaces that form smooth, glassy pellets when water cooled. Flue gas desulfurization (FGD) residuals are the material that forms from the process of reducing sulfur dioxide emissions from a coal-fired boiler

that can be a wet calcium sulfite or calcium sulfate sludge or a dry powdered material that is a mixture of sulfites and sulfates. The ash may also contain lightweight, inert, hollow spheres (i.e., cenospheres) consisting mainly of silica and alumina and filled with air or inert gas. Depending on the combustion process, fluidized bed combustion ash and other scrubber residues must also be handled.

Coal ash contains concentrated amounts of the coal that has been burned, with the exception of those that have oxidized in the combustion

process and released as H_2O , CO_2 , and products of incomplete combustion (PICs) from vents and stacks. However, the ash also can contain compounds that do not even exist in the parent coal or only in minute quantities. Bromide presents an example. The wastewater from wet FGD has elevated bromide concentrations. Bromine (Br) concentration in coal is about 10 ppm, which is primarily converted to volatile hydrogen bromide (HBr) during combustion and, when cooled, to Br gas. Very little of the residual Br finds its way to bottom or fly ash, and without FGD, most of the Br is released into the air as vapor [8]. However, with FGD, much of the Br finds its way to the wastewater, which is either discharged to surface waters or impounded in ash ponds. Also, Br is added to fly ash to collect mercury (Hg) that would otherwise be released to the air. Fly ash is not effective in sorbing Hg, but becomes an alternative to expensive sorbents like activated carbon, if treated with Br [9]. Thus Br concentrations rise in surface waters with the discharges, but also in groundwater with seepage from landfills, ponds, and pits. Drinking water intake is threatened, whether from a stream, an alluvial aquifer, or from other wells. The increased concentrations of Br in surface waters and drinking water systems can react with organic compounds, which in turn increases the concentrations of brominated disinfection by-products [8], for example, brominated trihalomethanes and brominated haloacetic acids, which have been associated with various health effects, including possible micronuclei frequency in lymphocytes, a biomarker for DNA damage and cancer risk [10].

Coal combustion residuals (CCRs) represent the largest amount of industrial wastes generated in the United States. The 10,000 tonnes of CCRs generated per year from 470 electric generating plants consist of bottom ash, fly ash, boiler slag, and by-products from FGD. Surface impoundments (ash ponds; see Fig. 7.6) and landfills hold half of the CCRs [7, 11]. If the effluent from ash is released into a surface waterbody

in the United States, the amount and type of effluent is limited by the National Pollutant Discharge Elimination System (NPDES) and requires an NPDES permit. Since this effluent very likely contains highly toxic metals and other contaminants, the permit process is complicated beyond a single effluent limitation threshold and requires that other factors, including background concentrations and characteristics of the receiving waterbody, be taken into account. For example, the U.S. EPA [12] applies a formula to calculate waste load allocations and to find the in-stream pollutant concentration (C_r) in mg L^{-1} in the stream reach after complete mixing occurs:

$$C_r = \frac{Q_d C_d + Q_s C_s}{Q_r} \quad (7.3)$$

where Q_d = waste discharge flow in units commonly used by US environmental engineers, that is, million gallons per day (MGD) or cubic feet per second (cfs); C_d = pollutant concentration in waste discharge (mg L^{-1}); [7] Q_s = background stream flow in million gallons per day (mgd) or cubic feet per second (cfs) above point of discharge; C_s = background in-stream pollutant concentration in mg L^{-1} ; and, Q_r = resultant in-stream flow after discharge (mgd or cfs).

This and similar equations are used by permitting authorities as part of the process in calculating water quality-based limits. If a value of zero is used for the ambient concentration for a pollutant (C_s) in the equation, the permitting authority can establish an entire limit on discharge. The EPA is aware that the resulting limit would not account for upstream background concentrations of the pollutant [12]. Depending on the pollutant, the background concentration is almost never zero, so the limit would not prevent an in-stream exceedance of the water quality criteria. In addition, some of the released pollutant is likely to come from nonpoint and other sources besides the direct



FIG. 7.6 Coal ash staging area. The ash slurry is pumped from the power plant and released into an ash impoundment. Courtesy of U.S. Environmental Protection Agency, *Coal Ash (Coal Combustion Residuals, or CCR)*, 2018, March 8, 2018. Available from: <https://www.epa.gov/coalash>.

discharge of the effluent, especially seepage from the ash storage system [12]. Thus handling CCRs requires coordination among water quality, air quality, and waste management

authorities. Indeed, failures of ash storage systems can involve direct and indirect releases into surface and groundwater (see Discussion Box: Dan River Ash Pond Failure).

DAN RIVER ASH POND FAILURE

On February 2, 2014, over 35,000 tonnes of coal ash spilled from Duke Energy's Dan River Steam Station's ash pond (Fig. 7.7) into the Dan River in

Eden, North Carolina (Fig. 7.8). The ash remained visible in a reservoir 80 miles downstream from the spill for days after the coal ash spill. The



FIG. 7.7 Breached ash pond released coal ash and coal ash wastewater into the Dan River. Courtesy of U.S. Fish and Wildlife Service, *Natural Resource Damage Assessment and Restoration for the Dan River Coal Ash Spill*, 2018, March 8, 2018. Available from: <https://files.nc.gov/ncdeq/Coal%20Ash/documents/Coal%20Ash/20140609%20FINAL%20Dan%20River%20cooperative%20NRDAR%20factsheet.pdf>.

DAN RIVER ASH POND FAILURE (cont'd)

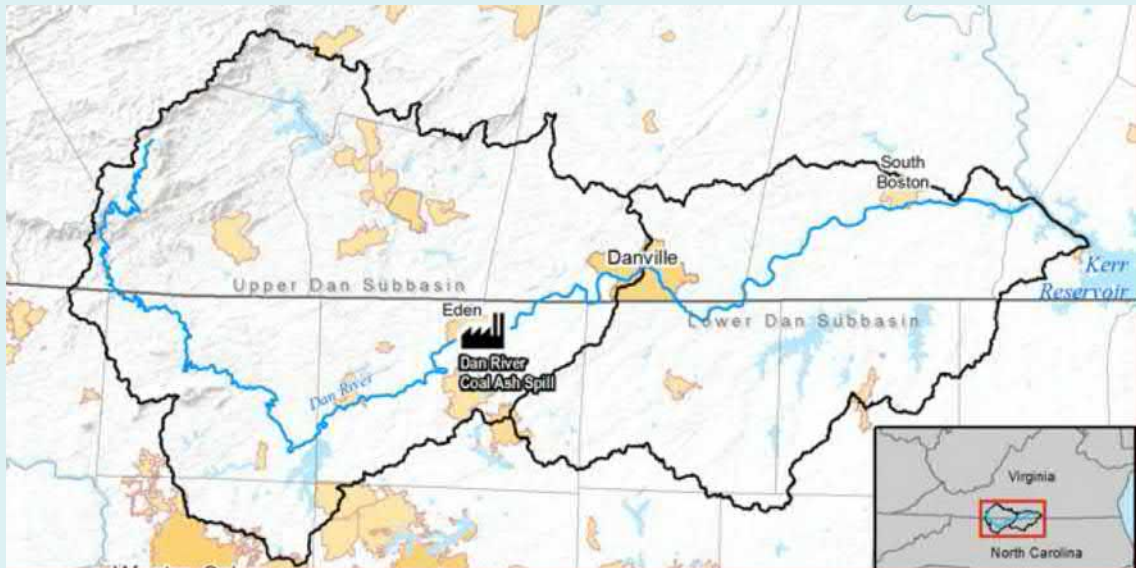


FIG. 7.8 Location of ash pond spill. Courtesy of U.S. Fish and Wildlife Service, Natural Resource Damage Assessment and Restoration for the Dan River Coal Ash Spill, 2018, March 8, 2018. Available from: <https://files.nc.gov/ncdeq/Coal%20Ash/documents/Coal%20Ash/20140609%20FINAL%20Dan%20River%20cooperative%20NRDAR%20factsheet.pdf>.

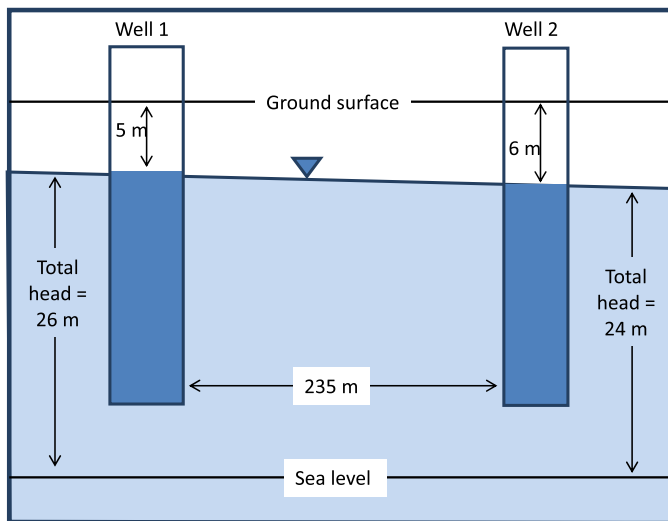
day after the spill, the North Carolina Department of Environment and Natural Resources, the Virginia Department of Environmental Quality, the U.S. Fish and Wildlife Service, and the U.S. Environmental Protection Agency, along with the utility, Duke Energy, initiated a unified command to address the spill, including technical assistance, oversight, data management, and environmental sampling and analysis. Other agencies eventually became involved in a massive effort to protect human health and the environment and guide the cleanup. These include the U.S. Army Corps of Engineers, North Carolina Department of Public Health, Virginia Department of Health, as well as county and local agencies from communities along the Dan River and within the Kerr Reservoir watershed [7].

An extensive breach such as this threatens both public health and ecosystems; metals and

other contaminants can reach drinking water supply intakes. The Dan River basin is a recreation area for fishing, boating, and wildlife viewing. The river is a vital habitat area for fish and wildlife, which include the endangered Roanoke logperch (*Percina rex*) and the James spiny mussel (*Pleurobema collina*), along with a species currently under consideration for protection, that is, the green floater (*Lasmigona subviridis*), a freshwater mussel [13].

On May 22, 2014, EPA and Duke Energy entered into an Administrative Order on Consent (AOC). Under the requirements of the AOC, the utility removed coal ash that had accumulated at the Schoolfield Dam, Town Creek Sand Bar, and at both the Danville and South Boston water treatment facilities. The removal action was completed in July 2014, and an estimated 4000 cubic yards of coal ash were removed.

FIG. 7.9 Hydraulic gradient between two wells. The difference in head is 2 m over 235 m, so the hydraulic gradient = $\frac{\partial h}{\partial x} = \frac{26 \text{ m} - 24 \text{ m}}{235 \text{ m}} = 0.0085 \text{ m m}^{-1}$ [1]. Modified from North Carolina Department of Environment and Natural Resources, *Groundwater, Aquifers & Confining Beds*, 2018, March 6, 2018. Available from: <https://www.ncwater.org/?page=560>.



Placing the wastes in a pit or other storage system can allow mercury (Hg), lead (Pb), arsenic (As), and other toxic metals and metalloids to migrate. For example, they can reach groundwater, a major source of drinking water for much of the world. An ash pit that is upgradient from a well can contaminate personal and municipal well water (see Fig. 7.9). Water stands in a well at a particular level, known as hydraulic head (h). Groundwater flows in the direction of decreasing head. The change in head measurement is the hydraulic gradient, $\frac{\partial h}{\partial x}$.

The capability of a fluid to move through underground materials is known as hydraulic conductivity (K). The various strata under the earth's surface may be consolidated rock or unconsolidated materials, like soil, sand, or gravel. Most commonly, however, the movement of groundwater is through the unconsolidated materials, that is, porous media. Darcy's Law is an empirically derived equation for the flow of fluids through a cross-section of porous media (A). It states that the specific discharge, Q , is directly proportional to the K and hydraulic gradient:

$$\text{Darcy's Law: } Q = -KA \frac{\partial h}{\partial x}.$$

The law assumes that flow is laminar and that inertia can be neglected. Thus if $K = 0.5 \text{ m s}^{-1}$, $\frac{\partial h}{\partial x} = 0.0085 \text{ m m}^{-1}$, and $A = 500 \text{ m}^2$, then $Q = 2.125 \text{ m}^3 \text{ s}^{-1}$. Thus if a leak has produced a plume, the aquifer is being contaminated at a rate of $2.125 \text{ m}^3 \text{ s}^{-1}$ (see Fig. 7.10).

4 COAL MINING WASTES

Coal mining can lead to problems similar to other extraction activities (see Chapter 6). Mining can either be by surface or underground, shaft mining (see Fig. 7.11). Both mining types destroy habitats and lead to surface and groundwater contamination, for example, when metals and other substances are leached in piles and mined areas, whereupon they are transported to surface waters.

4.1 Underground Mining

Underground or shaft coal mining generates various kinds of wastes and pollution. The mining processes lead to contaminated groundwater and coal fires. A coal mine fire smolders,

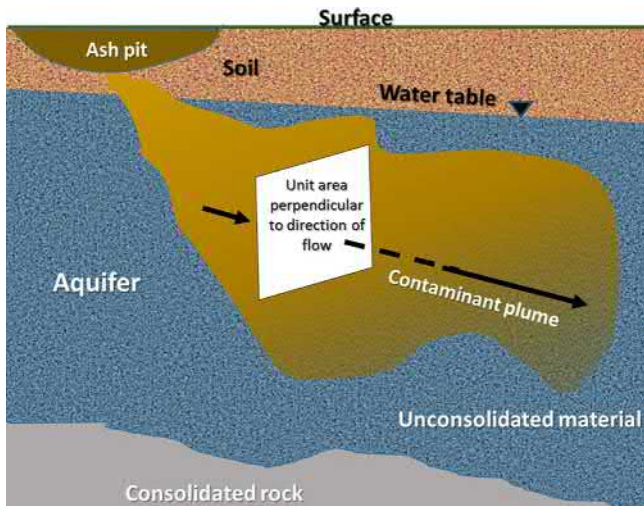


FIG. 7.10 Plume of pollutants flowing from an ash pit into a drinking water aquifer. The plane perpendicular to groundwater flow is used to calculate the movement, that is, flux of the plume.

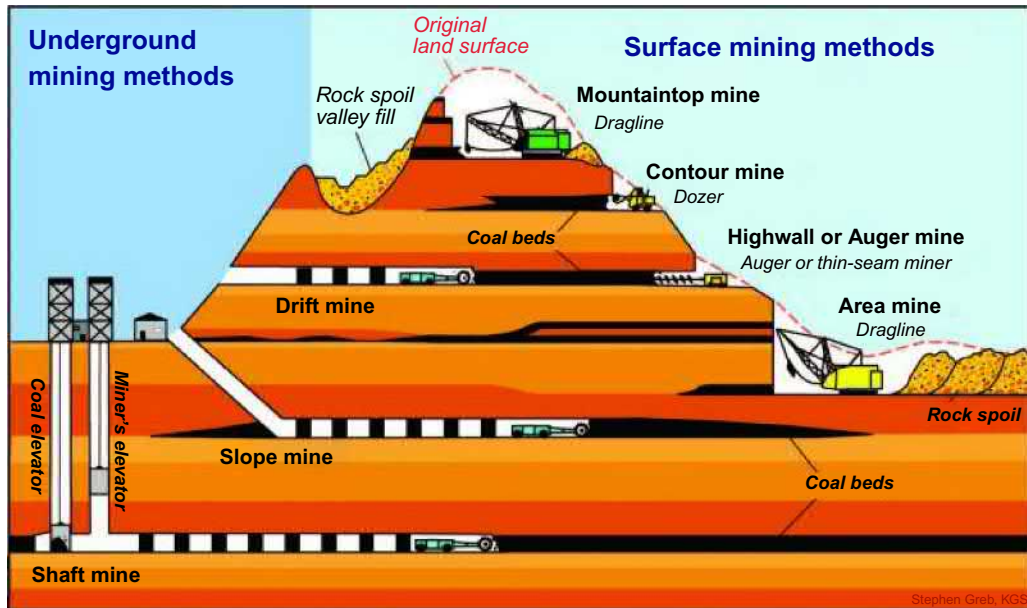


FIG. 7.11 Underground mining (left) and surface mining (right) methods of extracting coal. Courtesy of U.S. Environmental Protection Agency, *Basic Information about Surface Coal Mining in Appalachia*, 2016, March 8, 2018. Available from: <https://www.epa.gov/sc-mining/basic-information-about-surface-coal-mining-appalachia#what>.

since oxygen levels are low, meaning they can burn for many years. This presents a serious problem from many aspects: economical (burning a vital commodity), environmental (emitting

vast amounts of greenhouse gases— CH_4 , CO_2 and mercury), dangerous subsidence, and toxic.

Underground fires are very difficult to extinguish since it is almost impossible to keep

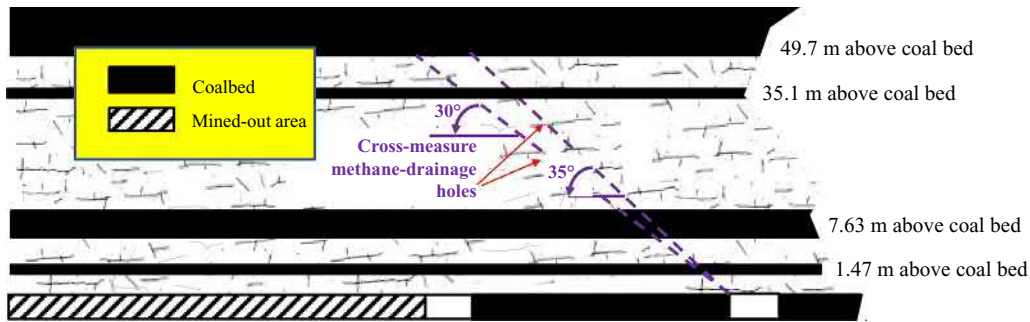


FIG. 7.12 Section view of cross-measure methane drainage holes in a coal mine ventilation system. Data from A. Smith, W. Diamond, T. Mucho, J. Organiscak, *Bleederless Ventilation Systems as a Spontaneous Combustion Control Measure in US Coal Mines*, 1994; B. McKenney, J. Rennie, *Longwall Ventilation With Methane and Spontaneous Combustion-Pacific Colliery. Paper in Fourth International Mine Ventilation Congress (Brisbane, Australia, July 3-6, 1988)*, Aust. Inst. Min. and Met., Melbourne, Australia, 1988, pp. 617-624.

oxygen from the fire. The vast room and pillar systems almost always are connected to the surface by fissures and cracks. Flooding the mines with water and slurries has been ineffective, since the fire simply finds alternative pathways in the leaky underground strata. Even if technically possible, suffocating fires can introduce safety risks at active mines, for example, miner safety and postignition fire suppression. To ensure sufficient oxygen levels and low toxic gas concentrations the mine's ventilation systems require methane drainage holes to control methane at the face. In many abandoned mines, cross-measure holes (see Fig. 7.12) were the most common types. These systems are one reason that oxygen remains available to these fires [14]. Internationally there are probably many hundreds of coal fires presently burning and countries such as Australia, Canada, China, Germany, India, Indonesia, New Zealand, Norway, South Africa, and the United States have documented details of ongoing fires. It has been estimated that these fires contribute to at least 3% of the world's annual emissions. For example, fires from China's coal mines presently release about 1×10^9 t (billion metric tonnes, t) of CO_2 to the atmosphere every year. Estimates put India's coal mine fire releases to

be about 50×10^6 t. This accounts for as much as 1% of all carbon greenhouse gas releases. This is about the same as the CO_2 released by all of the gasoline fuel automobiles in the United States. Engineering solutions that reduce these emissions would actively improve the net greenhouse gas global flux. Some US coal mine fires have burned for more than a century.

4.2 Surface Mining

Surface mining of coal involves the extraction and transfer of massive amounts of overburden to reach a coal seam. Hilltop mining removes the overburden from the top of a mountain and deposits the waste material in nearby valleys (see Fig. 7.13) [15]. This greatly alters streamflows, topography, and terrain features, but among the most crucial problems is that the burial of headwater streams destroys ecosystems. Hilltop mining destroys forests and woodlands, decreases biodiversity, and adversely affects many species (see Fig. 7.14).

Hundreds of streams near US Appalachian coal fields have experienced:

- (a) an increase of minerals in the water, for example, zinc, sodium, selenium, and sulfate



FIG. 7.13 Mountain top mining in West Virginia. *Courtesy of U.S. Environmental Protection Agency, 2012, March 16, 2012. Available from: <http://www.epa.gov/region03/mtntop/index.htm>.*

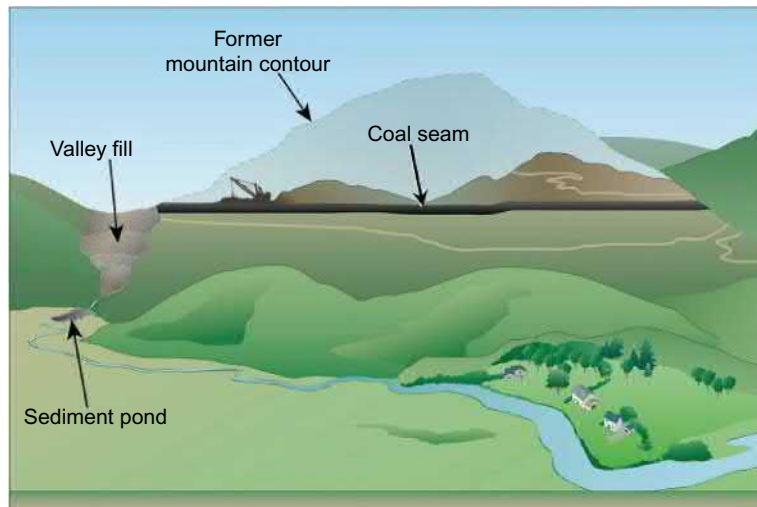


FIG. 7.14 Change in terrain and hydrology as a result of coal and overburden removal by mountaintop mining. *Courtesy of U.S. Environmental Protection Agency, Basic Information about Surface Coal Mining in Appalachia, 2016, March 8, 2018. Available from: <https://www.epa.gov/sc-mining/basic-information-about-surface-coal-mining-appalachia#what>.*

- which could have an impact on the fish, macroinvertebrates and other streams in watersheds below valley fills tend to have greater base flow,
- (b) wetlands destruction,
 - (c) forests broken into sections,
 - (d) impeded regrowth of trees and woody plants on regraded land in part due to compacted soils,
 - (e) increased the populations of grassland birds and snakes on reclaimed mine, but reduced populations of amphibians.

Other impacts of surface mines include esthetics, groundwater and surface water runoff contamination, noise, air quality (dust and mining pollutants), vibration, subsidence, as well as a devastating effect on the flora and fauna of the region [16].

In addition to habitat destruction, mining activities lead to explosions, subsidence, slurry spills, and chemical pollution both above ground and through groundwater. The chemical pollution results when soil and rock are broken, allowing migration of metals and other elements from the mining area in air (i.e., fugitive dust) and in water. One of the most common results from surface coal mines is an increase in acidity, in large part due to the sulfur being leached from the coal and overburden, and oxidized.

The most direct and immediately obvious toxicological effect of the switch to coal was acid mine drainage (see Fig. 7.15). Acid drainage is caused by the oxidation of metallic compounds such as the mineral constituent of rocks and soils that is often present in coal mine wastes and overburden. Streams affected by coal mine drainage are typically acidic (pH 2.5–6.0) and are characterized by high iron and sulfate concentrations. In addition, the iron, as ferric hydroxide, often precipitates as a fine flock that may coat stream bottoms and further affect aquatic life. Acid mine drainage may also leach toxic concentrations of metals such as copper, aluminum, and zinc from rocks and soils. The oxidation, or weathering, of pyrite and other metal sulfides is a natural process that may occur spontaneously on exposure of minerals to air, or it may be mediated by bacteria. Weathering of pyritic rock formations has resulted in naturally acidic streams in some localized areas of the Southeast United States [1, 17].

By the mid-1960s, a century of US surface mining had disturbed about 8000 km², including 21,000 km of streams (totaling 550 km²), 281 natural lakes (419 km²), and 168 reservoirs (168 km²) [18]. Coal mining accounted for 41% of the total disturbed lands, the bulk of pollution being from



FIG. 7.15 Iron hydroxide precipitate in a Missouri stream receiving acid drainage from surface coal mining. *Courtesy of D. Hardesty, Iron Hydroxide Precipitate (Orange) in a Missouri Stream Receiving Acid Drainage From Surface Coal Mining, Columbia Environmental Research Center U.S. Geological Survey, Ed., 2005.*

acid mine drainage in the East and the Midwest portions of the United States. Current US surface mining regulations mandate the restoration of disturbed lands [1].

Eastern and mid-western coals contain significant quantities of sulfur, so their combustion reactions release large quantities of SO₂, the major component of acid precipitation, to the atmosphere. Most of the high-sulfur coal consumed in the United States during this century has been used to make steel and to generate electricity in the East and Midwest. From there,

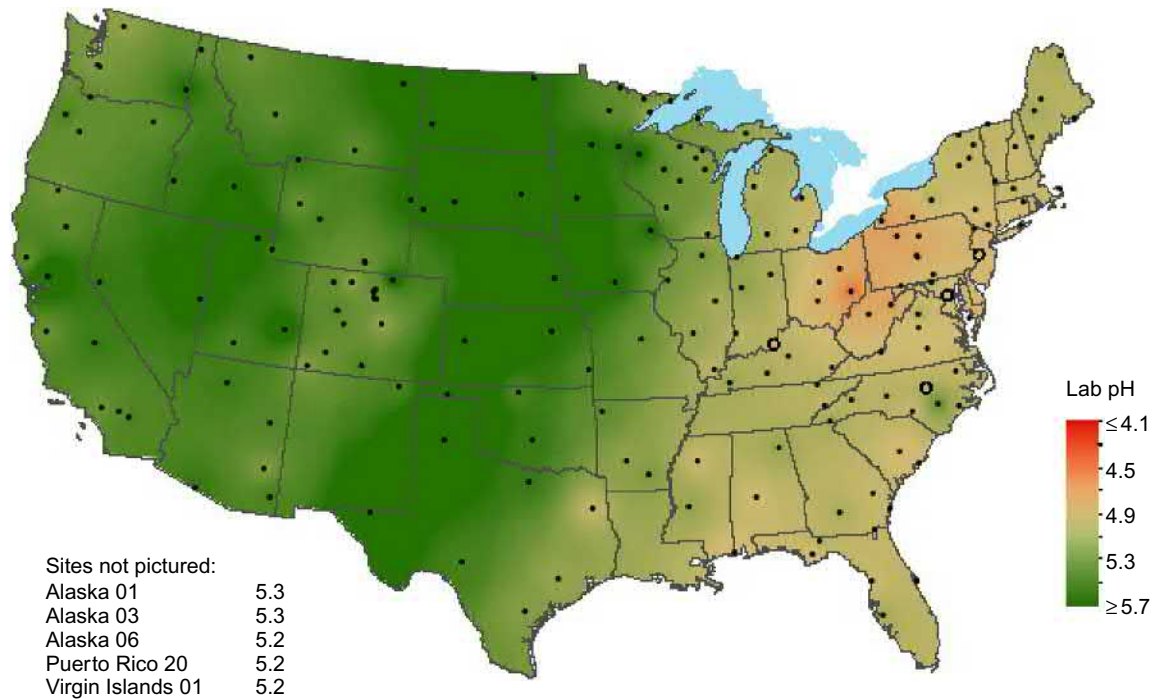


FIG. 7.16 US rainfall pH, 2011, as weighted mean values based on measurements at about 200 sites maintained by the National Acid Deposition Program. *Courtesy of Illinois State Water Survey. University of Illinois at Urbana-Champaign, NADP Data Report 2013-01, National Atmospheric Deposition Program: 2012 Annual Summary, 2013.*

atmospheric pollutants responsible for acid precipitation are transported northward and eastward by prevailing winds and storms. These trends are reflected in the geographic distribution of rainfall pH (Fig. 7.16). There are a number of sources contributing to acid precipitation, including those from automotive exhausts, but emissions from coal-fired electric generating plants presently constitute the largest source of atmospheric SO_2 in North America.

Areas with underlying crystalline rock, shale, and sandstone are more prone to acidification than those underlain by rock systems that buffer the acids, for example, limestone and other carbonate-rich rock. Potentially sensitive areas are widely distributed in North America and include much of the Appalachian Mountains, where rainfall is most acidic (Fig. 7.16); the

Canadian Shield region of the upper Midwest (i.e., the northern parts of Michigan and Wisconsin, as well as eastern Minnesota and parts of eastern and central Canada); the higher elevations of the Sierra Nevada, Rocky Mountains, and Cascade Range; and parts of the Ozark and Ouachita uplands, mid-Atlantic Coastal Plain, and Florida. Buffering by ions in groundwater and constituents leached from watersheds makes large lakes and rivers at lower elevations less susceptible to acidification than smaller, higher elevation lakes and streams [1, 19].

The interactions of ions in precipitation (i.e., H^+ , SO_4^{2-} , NO_3^{-2}) with organic and inorganic constituents of soil and water affect toxicity. Particularly important is the leaching of potentially toxic elements, especially aluminum, from rocks and soils by acidic precipitation. Toxicity

attributable to pH and aluminum is often episodic, occurring during high surface water discharge in the spring months. Spring is also the time when spawning and larvae releases occur for many aquatic organisms, making them vulnerable to reduced pH conditions. By definition, acid rain is rainfall with a pH lower than about 5.0; the pH of distilled water in equilibrium with atmospheric CO₂ is 5.6, but other atmospheric constituents tend to make rainfall more acidic even in areas unaffected by air pollution. In addition to sulfur, the combustion of coal emits other potentially toxic elements, including arsenic, cadmium, lead, mercury, and selenium. Cadmium and selenium are concentrated in coal ash, from which they may be leached into surface waters and accumulated to toxic concentrations by aquatic organisms. Mercury, along with selenium, and other elements in coal are released into the atmosphere in stack emissions that can move long distances. Mercury and selenium readily bioaccumulate in birds, mammals, and predatory fishes. Mercury is generally released from point sources, for example, caustic soda, that is, sodium hydroxide (NaOH) plants and paper mills. Bioaccumulation of mercury in remote lakes in the Northeast seems to indicate that atmospheric transport and natural chemical processes tend to keep mercury available for accumulation by organisms. Coal-fired electric generating plants are the greatest sources of atmospheric mercury, while other important sources include municipal and hospital waste incinerators [1].

In addition to and exacerbated by decreasing pH, metal contamination also occurs from mining. For most metals, the chemical form determines just how toxic it is. The form also determines how readily the metal moves in the environment and how rapidly it is taken up and stored by organisms. The chemical form is determined by the oxidation state or valence of the metal. Metals are the elements listed on the left side of the periodic table of elements. They form positive ions (cations), are reducing agents, have low electron affinities, and have

positive valences (oxidation numbers). Nonmetals, listed on the right side of the periodic table, form negative ions (anions), are oxidizing agents, have high electron affinities, and have negative valences. Metalloids have properties of both metals and nonmetals, but two environmentally important metalloids, arsenic (As) and antimony (Sb) behave much like metals in terms of their toxicity and mobility, so they are often grouped with the heavy metals.

At some concentration, every element except those generated artificially by fission in nuclear reactors is found in overburden and soils. This is true for toxic elements, such as the heavy metals, mercury (Hg) and lead (Pb), which are known to be neurotoxic and to cause other human health effects. The global mass balance of these metals, however, does not change; only the where and what form (i.e., chemical species) can be changed. When concentrated and made bioavailable to humans and other organisms, such as from extraction and refining processes, they present major threats to public health and the environment [1].

5 THE FUTURE

Waste managers and other environmental professionals will be tasked with the proper handling of coal-related wastes for the foreseeable future. The wastes come from many stages of deriving electrical energy from coal, from extraction to combustion to ash storage and beyond. Thus any waste planning must be based on strong science and feasible solutions.

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Further Reading

Effect of Waste on Ecosystems

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1 INTRODUCTION

Waste management, like all environmental endeavors, involves stressors and receptors. The stressors are the agents that must be eliminated, decreased, or otherwise managed, such as the waste itself or certain constituents of the wastes, for example, heavy metals, organic compounds, microbes, or energy. The receptors, by definition, receive the harm caused by the stressors. Environmental receptors are usually categorized as human or ecological, but can also be abiotic, such as building materials and national monuments.

Depending on the type of waste, the reason for concern varies. If a waste contains hazardous

chemicals or microbes that may reach humans in sufficient quantities it is a threat to public health. A so-called nonhazardous waste may also be a threat to public health if quantities are sufficiently high. The amount that is a threat depends on the persistence of the waste components. If they breakdown rapidly by natural processes or are treated properly, the hazard is curtailed. Similarly, wastes can threaten ecosystems in sufficient quantities.

Arguably, waste management gives primacy to human receptors and the protection of public health, especially in reducing exposures to chemical and microbial agents. Public welfare is also among the most visible indicators of poor waste management, such as the unsightliness of an open

dump, or the disfiguring of a landscape from littering, or marring the curb appeal by late or improper waste collection. This means that ecosystems may not be the first class of receptors of interest to waste managers, but they are indeed very susceptible to wastes. This chapter addresses how ecosystems are diminished and damaged by wastes and how this harm can be avoided.

2 ECOSYSTEM ASSESSMENT

Waste management is often directed at the source of pollution. Indeed, some of the waste management control technologies described in this book are actually real or potential sources of pollution. For example, an engineered landfill receives wastes that had been distributed throughout a larger area and consolidates the wastes at a central point (see Chapter 4). As such, the pollutants from the entire have been concentrated at a single site (see Fig. 8.1). There are many advantages of a centralized waste system over distributive sources, including ease and efficiency of treatment and other engineering controls. Conversely, the amount of hazardous substances at the central site is more likely to exceed thresholds of environmental quality, especially for substances that may have been naturally degraded by microbial populations at lower concentrations [1]. These concentrations may cause problems in ecosystems that would not necessarily bother humans, given safeguards like drinking water treatment. For ecosystems, however, even small releases can reach habitats, especially if they are built in or near sensitive habitats, for example, coastal zones [2]. In some cases, the waste treatment may introduce new, even more toxic compounds, such as when municipal solid waste (MSW) is incinerated and products of incomplete combustion, like dioxins and polycyclic aromatic compounds, are dispersed and reach habitats well removed from the site [3–7]. Thus the waste manager must be aware of potential

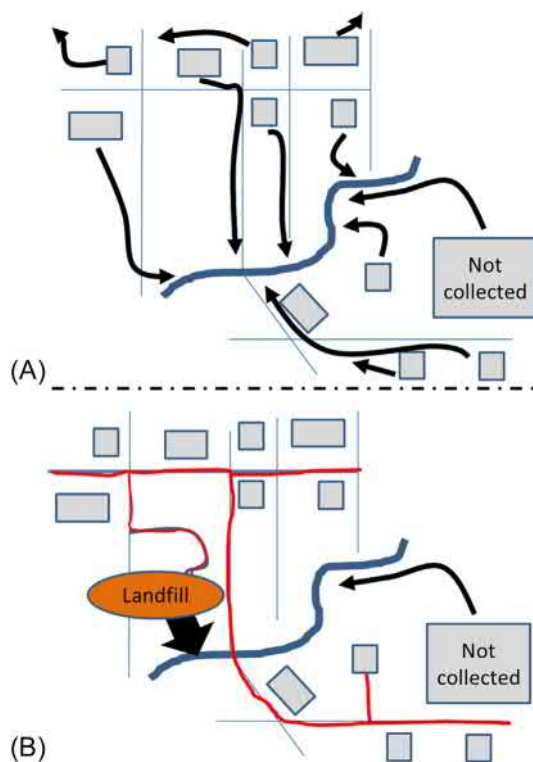


FIG. 8.1 Change of sources of a chemical contaminant to a river ecosystem before and after waste collection and transport to a landfill. The black arrows indicate the pathway of the pollutant. Before the landfill, the chemical could travel through many pathways from many sources, for example, subdivisions and other properties (A). After wastes are transported to the landfill, the landfill becomes the principal source (B), so its potential release is much larger. However, since landfills are designed to slow the flow of leachate and to treat the wastes, the actual amount reaching the stream should be substantially decreased. (A) is an example of distributive waste system and (B) is an example of a centralized waste system.

threats to ecosystems when selecting and operating transport, storage, and treatment facilities.

2.1 Ecosystem Risk and Sustainability

Two common types of metrics for evaluating environmental quality are risk and sustainability. Risk is the likelihood that an adverse effect

will occur. Sustainability is the likelihood that beneficial aspects will continue. Managers and engineers apply their crafts to decrease risk and to continue, and hopefully enhance, the benefits of what they manage and design, respectively. For ecosystems, this means that risks must be minimized and efficient, regenerative mechanisms are protected. Not only must chemical, physical, and biological threats and hazards be kept in check, but system resilience must be maintained so that the benefits are sustained. Sometimes it is a matter of simply leaving things alone, that is, not siting a landfill in or near a wetland, but other times affirmative actions must be put in place, for example, protecting the habitat of endangered species from runoff from upstream developments (see Chapter 33).

Ecological risk assessment (see Fig. 8.2) characterizes exposure and ecological effects to an ecosystem and its components. Unlike the sequential process employed for human risk assessments conducted in the last two decades of the 20th century, the eco-risk framework

considers exposure and effects together during problem formulation. [8] The final step of both the human and ecosystem risk assessment processes is referred to as “characterization” to mean that “both quantitative and qualitative elements of risk analysis, and of the scientific uncertainties in it, should be fully captured by the risk manager.” [9] True to a “systems” perspective, the eco-risk process allows for an integration of research with risk assessment, bolstering the science that underpins risk management decisions. The problem formulation step in the ecological framework has the advantage of providing an analytic-deliberative process early on. That is, it combines sound science with input from various stakeholders inside and outside of the scientific community.

The ecological risk framework calls for the characterization of ecological effects instead of hazard identification used in human health risk assessments. This is because the term “hazard” has been used in chemical risk assessments to connote either intrinsic effects of a stressor or a

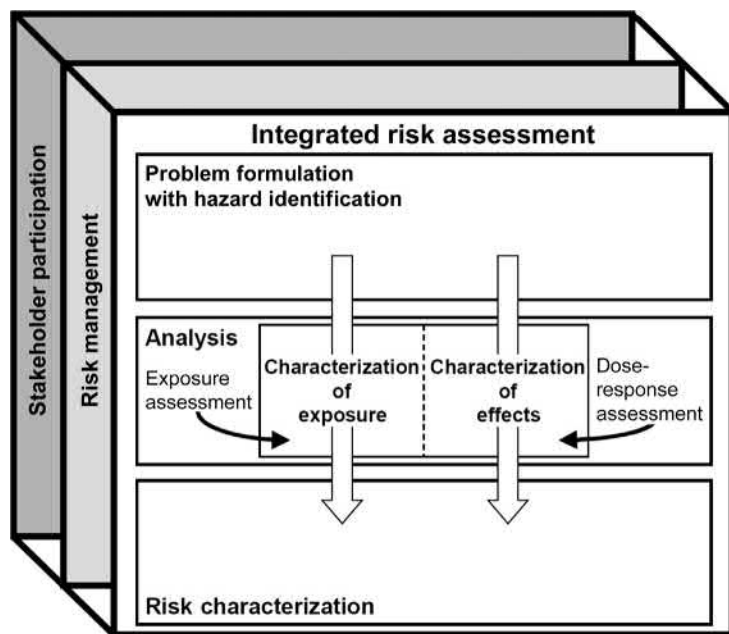


FIG. 8.2 Framework for integrated human health and ecological risk assessment. Sources: World Health Organization; and U.S. Environmental Protection Agency (1998).

margin of safety by comparing a health effect with an estimate of exposure concentration.

The waste manager should be aware of work being done not only by solid waste organizations in the waste jurisdiction, but must also confer with experts in departments of natural resources, public works, transportation, engineering, subdivision regulations, as well as the county extension and other soil conservation groups. Each of these organizations and others varies in their perspectives, but offers insights into ways to protect ecosystems. They are also likely to have experienced successes and failures that may prevent mistakes. Waste management encompasses a widely diverse community that varies in its perception of the importance of ecosystems. Indeed, ecosystems have both intrinsic and instrumental value. An ecologist may perceive the former as most important, but for the engineer it may be the latter, i.e., ecosystem goods and services. However, the waste manager and engineer must optimize on the basis of many factors and constraints, many outside the physical science “comfort zone.” Scientist and philosopher Jacob Bronowski [10] reminds us:

All engineering projects are communal; there would be no computers, there would be no airplanes, there would not even be civilization, if engineering were a solitary activity.

Waste management is translational. It draws from a wide array of expertise. The key is choosing and implementing the best plans and technologies to achieve the desired outcome with minimal negative outcomes.

2.2 Predicting and Managing Outcomes

So long as the variables and parameters of any system are sufficiently understood, the outcome is predictable. Actions to address MSW and other wastes can have far-reaching and long-term effects on ecosystems. These effects are seldom immediate or obvious given that ecosystems are comprised of diverse living and

nonliving systems. This means that many of the necessary variables are not well understood and nearly impossible to quantify, so the models and other methods that predict outcomes are, to varying degrees, weak and incomplete. Despite this, waste management must identify, characterize, and analyze various options in terms of ecological outcome. The key aspects of a sound ecological risk assessment is its ability [11]:

- to describe accurately and precisely the events and situation at hand;
- to consider the important associated and causative factors;
- to articulate completely the decisions that are to be made; and,
- to maintain objectivity, so that the assessment underpins comprehensive, fair and consistent decisions that leads to appropriate actions, outcomes, and consequences.

3 ECOSYSTEM STRESS

Ecosystems are harmed by physical, chemical, and biological stressors. The response to these stressors varies, but depends on both the severity and amount of stress and the sensitivity of the ecosystem compartments to the stress.

3.1 Ecosystem Failure Analysis

Predicting and managing outcomes is an exercise in applying available information to extrapolate and interpolate from the known to the less known. This is the nature of risk management models, science-based decision making, and forward trajectories. This is the flip side of trying to see why something happened, which is done using root cause analysis, decision trees, deconstruction/reconstruction, and failure analysis [12].

These are important tools to evaluate reliability of solid waste management systems. For example, a common technique in determining the availability and reliability, $R(t)$, of a waste

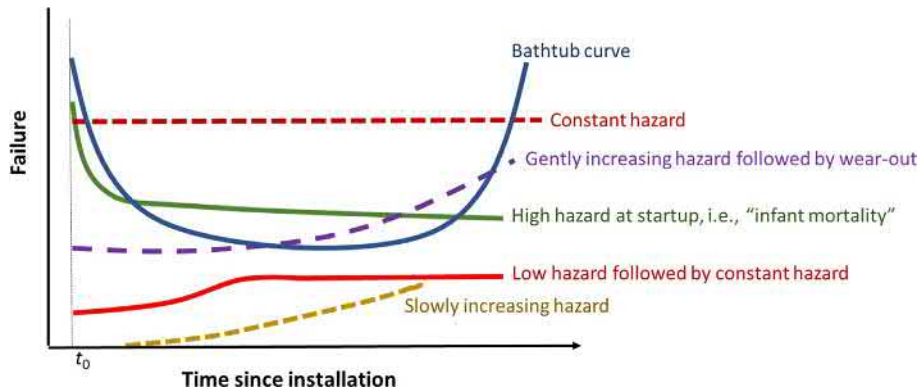


FIG. 8.3 Idealized patterns of reliability.

system is to calculate the mean time between failures (MTBF) [13]:

$$R(t) = \exp\left(-\frac{t}{\text{MTBF}}\right) = \exp(-\lambda t) \quad (8.1)$$

where t is the operation time and λ is the reciprocal of MTBF.

Engineers are familiar with failure, which is effectively the opposite of reliability. Failure can be stated as a probability. Survival analysis is an approach used to look at data up to the time of interest. Since our time of interest is the time until failure, the survival function $[S(t)]$ is the same as $R(t)$. A hazard is the conditional probability of failure of a currently working system. Thus the failure can be expressed as a hazard function, that is, the instantaneous rate at which events happen if there are no previous events. The hazard function can be measured over time, for example, the lifetime of a facility's components, for example, the cells in a landfill or the kiln in an incinerator. The change of the hazard function with time produces various patterns (see Fig. 8.3), depending on the type of facility and equipment, as well as the operating conditions. The bathtub curve is a common pattern for engineered systems [13–15], that is, high failures rates at the outset, especially for unproven technologies, followed by the optimal life with lowest failure rates, and ending with failures

at the end of the useful life due to wear-out and senescence.

Recently, numerous software packages have become available to the waste manager to calculate $R(t)$, notably, reliability, availability, maintainability, and safety (RAMS) software [16]. This goes by numerous terms, but managing wastes to protect ecosystems falls under the province of "industrial ecology" [17–19]. The industrial ecology process includes identifying waste streams, the waste constituents of concern, and ways to address these concerns, for example, conversion technologies. The process also evaluates, together, the economic and environmental effects of using wastes and transformations that may occur during transport, handling, and processing. Depending on the various MSW input streams, the optimal methods will vary.

Ecosystems are even more complex than engineered systems¹ given the interrelationships among the abiotic and biotic features. As such, the idealized patterns in Fig. 8.3 are not representative of ecosystem response to stresses. In fact, concepts like carrying capacity, resilience, and sustainability are better indicators of ecosystem reliability. For example, an

¹ Some ecosystems are all or in part engineered, such as engineered wetlands and bio-retention systems. In this case, they are just as complex as natural ecosystems.

ecosystem may be functioning quite well until it reaches a stress threshold, at which point it may “crash” and no longer function. This is lesson of *Tragedy of the Commons*, espoused by Garrett Hardin (1915–2003), which has become a “must-read” in every introductory ecology course. In this article Hardin imagines an English village with a common area where everyone’s cow may graze. The common is able to sustain the cows and village life is stable, until one of the villagers figures out that if he gets two cows instead of one, the cost of the extra cow will be shared by everyone, while the profit will be his alone. So he gets two cows and prospers, but others see this and similarly want two cows. If two, why not three—and so on—until the village common is no longer able to support the large number of cows, that is, the ecosystem exceeded its carrying capacity (see Fig. 8.4). Given the complexity of ecosystems, a crash may still occur with other changes in conditions, for example, drought, introduced and opportunistic species, dredging, landfill leaching, wetland destruction, deposition of pollutants from

incineration, and so on. Thus even though the waste manager is not likely to be engaged in animal husbandry, Hardin’s caution applies equally to solid waste decisions.

It is important to keep in mind that, even if the waste management system is efficient at waste handling, there is always the potential for attendant, undesired outcomes. Furthermore, even if a project is acceptable, there can still be an unacceptable cumulative outcome when viewing it in combination with all the other “acceptable” projects. In other words, waste management must recognize their projects within concept of systematic success. A multistep process can be used to approach the various types of risks that may result from any engineering application [20], but particularly in view of the impact on complex ecosystems:

1. Properly accounting for uncertainty [21];
2. Basing risks on different types of information and understanding the limitations of using other peoples’ data;
3. Comparing risks that may result consistently among the alternative actions [22, 23];

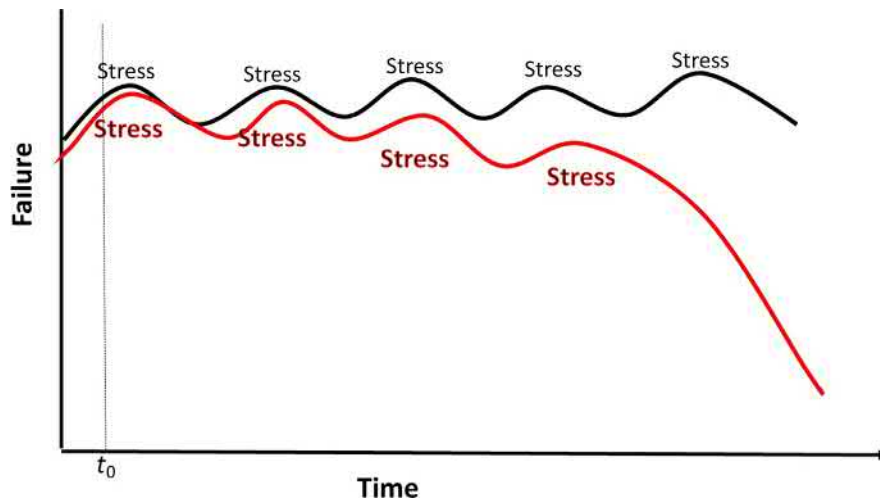


FIG. 8.4 Idealized failure of an ecosystem incremental stresses. The black line represents a system with relatively similar stresses over time, for example, equal number of grazing animals or tons of refuse in a landfill, where the system recovers. The red line represents a system in which the stresses increase over time, for example, increased number of grazing animals or tons of trash in a landfill every year. At some point, the system crashes. Note that the stresses do not have to be the same. For example, the number of grazing animals may stay the same, but drought or changes in biodiversity (e.g., from introduced plant species), the failure pattern may be similar to the red line.

4. Employing a tiered, intelligent, adaptive, and flexible approach to risk assessment, often beginning with a higher tier, scoping effort, and adding needed details as information is continuously reevaluated [24, 25];
5. Evaluating the value of information on which decisions will be based, including assignment of quality and relevance thresholds below which the data and information should be avoided or, at a minimum, given appropriate caveats.
6. Determining the approach to validate and evaluate the models and other tools used to assess the risks [26]; and,

Considering the cumulative risks from exposures to all types of stressors, that is, physical, chemical, and biological [27, 28], waste management decisions must consider the effect the actions will have on the integrity of ecosystems in time and space. A practical means of estimating this is to apply ecosystem indices and models [29].

4 ECOSYSTEM INTEGRITY

The integrity of ecosystems depends on proper waste management. This includes virtually every waste stream discussed in this book. For example, agricultural waste directly affects adjacent wetlands and other adjacent ecosystems when topsoil is lost after a precipitation event, the storm water holds and transports both suspended material (e.g., soil, debris) and soluble matter (e.g., organic and organic chemicals). Solids of any form can either directly enter surface waters or reach a storm sewer system. Thus proper management of agricultural, construction, transportation, and municipal wastewater supports ecosystem protection.

The material reaching an ecosystem is harmful in two ways. Firstly, it harms the integrity of the receiving systems, for example, increasing turbidity, suspended and dissolved solids content, and the organic load. Secondly, the material may contain constituents that can be inherently

hazardous to humans, wildlife and other biota (see Chapter 13).

The material in the runoff is collectively referred to as “sediment” which, when it enters a water body in substantial amounts, can substantially decrease the ability of light to penetrate the water column. Environmental engineers refer to this as increased turbidity, which is commonly measured lowering a Secchi disk, that is, 30-cm diameter disk into water until it disappears from view [30, 31]. This depth, known as the Secchi depth, is recorded as the turbidity score, which has been a mainstay in surface water assessments for the last century and a half [32]. The turbidity increases directly with sediment loading. As the sediment load increases, the growth capacity of aquatic plants and algae increases, and normal aquatic processes are altered. Notably, seasonal turnover and nutrient cycling in the surface waters change directly with increased solids concentrations and indirectly with decreased light infiltration and the attendant decline in photosynthesis rates.

Household hazardous wastes, such as insecticides, pesticides, paint, solvents, used motor oil, and other auto fluids are also frequently part of the sediment load. These are often highly toxic to aquatic life and human populations. Pathogenic microbes may be suspended or sorbed to suspended particles in water. Notably, *Escherichia coli* can cause major human health problems and indicate the presence of enteric bacteria, that is, those that grow in the intestines of animals, so they are also known as fecal coliform bacteria. Such microbial disturbances can also adversely affect other species, for example, aquatic and terrestrial animals in ecosystems. Sediment loading can change the species composition and diversity of lakes and other surface waters. For example, the increasing input of nitrogen, phosphorus, and other nutrients encourages the growth of algae, leading to algal blooms. When these algae die, they fall to the lake bottom. As they continue to decompose, more oxygen is demanded by the bacteria and abiotic processes, so the concentrations of dissolved oxygen (DO) decline. As a

result, fish and other organisms at higher trophic levels in the food chain are stressed. This can result in fish kills and complete alterations to aquatic habitats.

Thus an indication of agricultural and human waste, and other waste sources, for example, septic tanks or even poorly treated effluent from municipal waste water treatment systems, is also an indication of the interconnectedness between human activities and ecosystem integrity.

Waste jurisdictions have a mandate to protect the environment. Most often, one can assume that a waste authority's attitude toward environmental assessment would be better than that of other organization that had missions other than protecting the environment. Even waste jurisdictions, however, can become so project oriented and seemingly myopic that they fail to analyze objectively the possible downsides of a favored option. This may in part be due to the so-called view that "perception was reality." That is, by definition, since the authority has "public" or "environmental" or "management" in its name, it *had to be doing good things for the environment* and could never do bad things when it came to environmental protection. The author's own experience shows this is often not the case. Indeed, the overall objectives of writing the permits and building treatment plants and landfill are noble and, and overall, necessary. Nevertheless, these actions are not without their own environmental implications [33].

Heat exchange and balances provide an example of the need for systems thinking [34]. In the Midwestern and Western regions of the United States, the value of a fishable stream is directly related to water temperature. This is because water temperature is directly proportional to dissolved oxygen content, which is a limiting factor of the type of fish communities that can be supported by a water body. For example, a trout (*Salma*, *Oncorhynchus*, and *Salvelinus* spp.) stream is a highly valued resource that is adversely impacted if the mean temperatures increase. Rougher, less valued fish (e.g.,

carp, Order Siluriformes) can live at much lower ambient water body temperatures than can salmon, trout, and other cold-water fish populations.

Cumulative heat exchange provides a useful example of the need for a systematic approach to evaluate potential outcomes. The reasons behind whether an environment is supportive or hostile to organisms may be direct or indirect. The relationship between increased temperatures in surface waters and game fish populations provides an illustrative example. The added heat may directly stress the game fish population. That is, the fish simply cannot tolerate higher temperatures.

The stress may also be indirect, as the stress is derived from increased temperature that leads to a drop in dissolved oxygen (DO) concentrations in the water, which deems the water body hostile to the fish. Often, the adult fish may do well at the reduced DO levels, but their reproductive capacities decrease. Or, the reproduction is not adversely affected, but the survival of juvenile fish can be reduced.

Of particular concern to solid waste managers, the ecological stress may be further derived as a type of "second-order" change. For example, the increased temperature leads to greater concentrations of dissolved metals since aqueous solubility is directly proportional to temperature. If the leachate from a landfill or the plume from an incinerator is added to the mix, even more of these newly formed toxic, metallic compounds are formed that become available to the fish, either directly through the gills, since the compounds have become more soluble in water, or indirectly as food from benthos and other organisms. This is a first-order change. However, the reduced DO in combination with the increased concentrations of dissolved metals makes for redox conditions whereby the metals may be reduced. These reduced metal species can be particularly toxic to fish and other aquatic fauna. The organometallic species that are formed may also have an increased potential to bioaccumulate

and biomagnify in the food chain, meaning they will find their way to human food supplies. Thus increased temperature drives numerous aspects in a system. The change in temperature drives the systematic effects. That is, with the resulting decrease in DO, and increasing metal concentrations, both ecosystem function and human health are threatened. The synergistic impact of combining the hypoxic conditions with presence of reduced metal compounds leads to larger problems than if either condition existed alone.

Additional “orders” of stress can continue to occur, which may be predictable and modeled. If the underlying scientific principles are understood, this model may be deterministic. If probabilities of events and outcomes are known (e.g., from laboratory studies or observations of previous scenarios), they can be applied to each stress. As mentioned previously, failure analysis tools like event probabilities, decision trees, root cause analysis, and Bayesian belief networks can be used to predict the likelihoods of various outcomes. These networks can be perturbed to predict how the outcomes change under various scenarios, for example, disallowing heated effluents entirely, controlling the effluent to meet certain levels, controlling metal inputs and pH, and so on.

5 INDICES AND MODELS OF ECOSYSTEM STRESS

Wastes and their constituents that reach an ecosystem can lead to complex responses to increased input of materials. Physics, chemistry, and biology changes constantly in ecosystems. For example, light penetration decreases with increasing solids, which results from both chemical and biological interactions. As discussed throughout this book, dissolved oxygen (DO) can rise or fall depending on increased nutrient levels in the system. Since the biota have unique optimal ranges of growth and metabolism that varies among species, for example, algae will add some O₂ with

photosynthesis, but use some O₂ for metabolism, whereas the bacteria will generally be net consumers of molecular oxygen. In addition, the nutrients allow other microorganisms, especially bacteria to thrive, which increases the demand for O₂, making the water more amenable to larger plants, but less amenable to fish. Thus the chemistry, that is, nutrient load, directly affects the biology, and indirectly affects the physics, that is, light budget, of an aquatic ecosystem. In turn, the diminished light penetration further affects the chemistry directly because the reduced rates of photosynthesis reduced the amount of O₂ in the water, which indirectly affects the biological organization of the system.

The most widely applied environmental indices are those that follow the framework of an index of biological integrity. An index is a tool that combines a number of factors, that is, indicators, to provide greater meaning from these indicators. For example, data may be available about sediment, nutrient constituents in water, and rainfall. These may say little on their own about the vulnerability of an ecosystem but, perhaps, mathematical manipulations of the relationships between these data may provide some insights about the integrity and vulnerabilities of the system. Such systems must account for how the factors work together and against one another, i.e. synergies and antagonisms, respectively. An index or model should quantify the relative importance of the factors, that is, indicator weights and thresholds. This is a type of sensitivity analysis. For example, some factors are so important, that even if all other factors are acceptable, when they fall below a threshold, the system crashes. Such factors are referred to as minimum operators in models. An example is minimum sustainable flow, that is, if the flow falls below a threshold, fish populations cannot be sustained [10, 35, 36].

The factors needed for ecosystem indices and models are data limited. Measurements are always samples of the larger population, for example, a small volume of a river's water is

sampled for biological and chemical parameters. Thus models are needed to extrapolate from these samples, not only to a much larger volume, for example, a reach, but also to what may occur in the future. Such “if-then” scenarios must rely on mathematical manipulations, such as fuzzy processing, to move from imprecise data to ecosystem outcome estimates, such as: If <premise>, THEN <conclusion>: IF “stream flow is low” and “DO is low” THEN “trout population is small”

Fuzzy set theory allows the vague terms often used by ecologists, for example, low and small, to be better defined and quantified [37]. Tools like fuzzy processing can also be combined with GIS and other spatial tools to provide two- and three-dimensional decision support for waste managers [38–40].

5.1 Integrity

In biological systems, integrity is the capacity of a system to sustain a balanced and healthy community. This means the community of organisms in that system meets certain criteria for species composition, diversity, and adaptability, often compared to a reference site that is a benchmark for integrity. Although integrity is described by a “biological” index, for the reasons expressed in the previous paragraph, it is also a chemical and physical index. To varying degrees biological integrity indices include not only biological metrics, e.g., species abundance and diversity factors, but also chemical and physical features, for example, DO and turbidity. As such, biological integrity indices are designed to integrate the relationships of chemical and physical parameters with each other and across various levels of biological organization. They are now used to evaluate the integrity of environmental systems using a range of metrics to describe system.

Environmental stressors, including biological agents, can be modeled in one dimension. Such a unidimensional model links exposure to a stressor to the environmental outcomes across

levels of biological organization (see Fig. 8.5). The model dimension differs from complexity, i.e., a one-dimensional model may be more complex than a multidimensional model. Risk assessors, for example, often differentiate aggregate and cumulative exposure models; wherein an aggregate model includes all routes and pathways for a single stressor, whereas a cumulative model addresses all stressors that lead to an adverse outcome. So, an aggregate model for stressor with many exposure pathways and routes may be more complex than a cumulative model for an outcome caused by a limited number of stressors in which the routes and pathways are easily identified. Thus food webs and chains can be represented by one-dimensional models, e.g., a pesticide that enters an ecosystem, with exposures and effects that span multiple levels of biological organization to indicate the interrelationships within very complex biological systems. Tropic state models like these can also help to uncover the mechanisms that occur when these systems are perturbed [25]. Thus environmental indices and models combine attributes to determine a system’s condition (e.g., diversity and productivity) and to estimate stresses.

The original index of biotic integrity developed by Karr [41] was based on fish fauna attributes and has provided predictions of how well a system will respond to a combination of stresses. In fact, the index is completely biological, with no direct chemical measurements. As indicated in Table 8.1, the metrics also indicate indirectly those physicochemical factors that drive the biology, for example, the abundance of game fish is directly related to dissolved oxygen concentrations. As such, the metrics provide descriptions of an ecosystem’s structure and function. That is, the amount and types of biota are reflected in an index. The index also shows how well the ecosystem is functioning in terms of productivity, biodiversity, and other ecological performance measures.

An example of the data that are gathered to characterize a system is provided in Table 8.2.

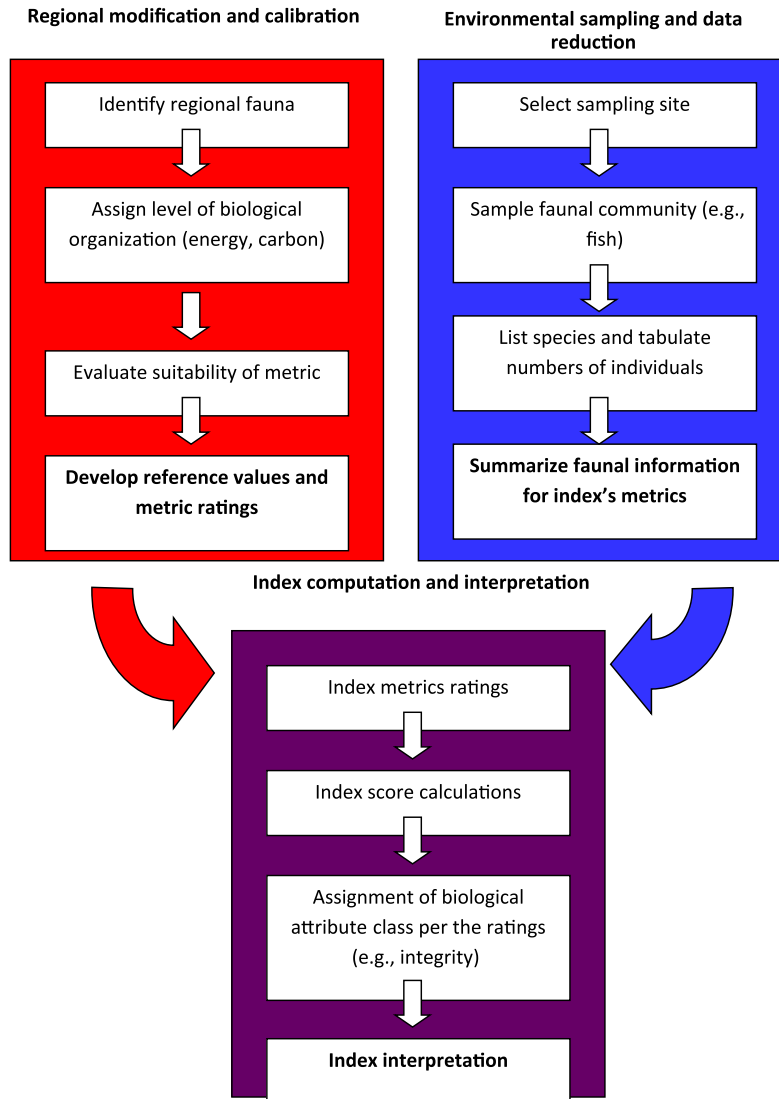


FIG. 8.5 Sequence of activities involved in calculating and interpreting an index of biotic integrity (IBI). Adapted from M.T. Barbour, J. Gerritsen, B.D. Snyder, J.B. Stribling, *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish*, US Environmental Protection Agency, Office of Water Washington, DC, 1999; J.R. Karr, *Biological monitoring and environmental assessment: a conceptual framework*, *Environ. Manag.* 11(2) (1987) 249–256.

The information that is gleaned from these data is tailored to the physical, chemical, and biological conditions of an area (in Table 8.2), for example, for large spatial regions. The information from a biologically based index can then be used to evaluate a system, as shown in Fig. 8.5.

Ecosystems involve biological, chemical, and physical processes at various scales and complexities. For example, a fish's direct aqueous exposure (AE in $\mu\text{g day}^{-1}$) is the product of the organism's ventilation volume, that is, the flow Q (in mL day^{-1}), and the compound's aqueous

TABLE 8.1 Biological Metrics Used in the Original Index of Biological Integrity

Integrity Aspect	Biological Metric
Species richness and composition	Total number of fish species (total taxa)
	Number of <i>Catostomidae</i> species (suckers)
	Number of darter species
	Number of sunfish species
	Number of intolerant or sensitive species
Indicator species metrics	Percent of individuals that are <i>Lepomis cyanellus</i> (Centrarchidae)
	Percent of individuals that are omnivores
Trophic function metrics	Percent of individuals that are insectivorous Cyprinidae
	Percent of individuals that are top carnivores or piscivores
	Percent of individuals that are hybrids
Reproductive function metrics	Abundance or catch per effort of fish
Abundance and condition metrics	Percent of individuals that are diseased, deformed, or that have eroded fins, lesions, or tumors (DELTs)

Source: J.R. Karr, *Assessment of biotic integrity using fish communities*, *Fisheries*, 6(6) (1981) 21–27.

concentration, C_w ($\mu\text{g mL}^{-1}$). The fish's exposure by its diet (DE , in $\mu\text{g day}^{-1}$) is the product of its feeding rate, F_w (g wet weight day^{-1}), and the compound's concentration in the fish's prey, C_p ($\mu\text{g g}^{-1}$ wet wt). If the fish's food consist of single type of prey that is at equilibrium with the water, fish's aqueous and dietary exposures and the bioconcentration factor (BC) can be calculated when they are equal:

$$AE = DE; \quad QC_w = F_w C_p; \quad BCF \frac{Q}{F_w} \quad (8.2)$$

The ventilation-to-feeding ratio for a 1 kg trout has been found [42] to be on the order of $10^{4.3} \text{ mL g}^{-1}$. Assuming the quantitative structure-activity relationship (QSAR) for the trout's prey is $BCF = 0.048$ times the octanol-water coefficient (K_{ow}), it appears that the trout's predominant route of exposure for any chemical with a $K_{ow} > 10^{5.6}$. Exposure must also account for the organism's assimilation of compounds

in food, which for very lipophilic compounds will probably account for the majority of exposure compared to that from the water. Even though chemical exchange occurs from both food and water via passive diffusion (Fick's Law relationships), the uptake from food, unlike direct uptake from water, does not necessarily relax the diffusion gradient into the fish. The difference between digestion and assimilation of food can result in higher contaminant concentrations in the fish's gut.

Predicting expected uptake where the principal route of exchange is dietary can be further complicated by the fact that most fish species exhibit well-defined size-dependent, taxonomic, and temporal trends regarding their prey. Thus a single bioaccumulation factor (BAF) may not universally be useful for risk assessments for all fish species. Indeed, the BAF may not even apply to different sizes of the same species.

FOR REFERENCE PURPOSES ONLY

TABLE 8.2 Biological Metrics That Apply to Various Regions of North America

Alternative IBI metrics	Midwestern United States	Central Appalachians	Sacramento-San Joaquin	Colorado Front Range	Western Oregon	Ohio Headwater sites	Ohio	Northeastern United States	Ontario	Central Corn Belt Plain	Wisconsin - Warm water	Wisconsin -Cold water	Maryland Coastal Plain	Maryland Non-Tidal
1. Total number of species	X	X	X	X				X		X			X	X
No. native fish species					X	X	X		X		X			
No. salmonid age classes ^a				X	X									
2. Number of darter species	X	X		X		X				X	X			
No. sculpin species					X									
No. benthic insectivore species								X						
No. darter and sculpin, species							X							
No. darter, sculpin, and madtom species											X			
No. salmonid juveniles (individuals) ^a			X		X			X						
Percent round-bodied suckers						X ^b								
No. sculpins (individuals)			X											
No. benthic species													X	X
3. Number of sunfish species	X			X		X				X	X			

Continued

FOR REFERENCE PURPOSES ONLY

TABLE 8.2 Biological Metrics That Apply to Various Regions of North America—cont'd

Alternative IBI metrics	Midwestern United States	Central Appalachians	Sacramento- San Joaquin	Colorado Front Range	Western Oregon	Ohio Headwater sites	Ohio	Northeastern United States	Ontario	Central Corn Belt Plain	Wisconsin - Warm water	Wisconsin -Cold water	Maryland Coastal Plain	Maryland Non-Tidal
No. cyprinid species					X									
No. water column species								X						
No. sunfish and trout species									X					
No. salmonid species			X							X				
No. headwater species							X							
Percent headwater species							X			X				
4. Number of sucker species	X				X	X		X		X	X			
No. adult trout species ^a			X		X									
No. minnow species				X			X			X				
No. sucker and catfish species									X					
5. Number of intolerant species	X			X	X	X		X			X	X	X	X
No. sensitive species							X			X				

FOR REFERENCE PURPOSES ONLY

[illegible]

Continued

FOR REFERENCE PURPOSES ONLY

TABLE 8.2 Biological Metrics That Apply to Various Regions of North America—cont'd

Alternative IBI metrics	Midwestern United States	Central Appalachians	Sacramento-San Joaquin	Colorado Front Range	Western Oregon	Ohio Headwater sites	Ohio	Northeastern United States	Ontario	Central Corn Belt Plain	Wisconsin - Warm water	Wisconsin - Cold water	Maryland Coastal Plain	Maryland Non-Tidal
8. Percent insectivorous Cyprinids	X												X	
Percent insectivores					X			X		X	X		X	X ^d
Percent specialized insectivores		X		X										
No. juvenile trout			X											
Percent insectivorous species						X	X							
9. Percent top carnivores	X					X		X	X	X	X	X		
Percent catchable salmonids					X									
Percent catchable trout			X											
Percent pioneering species							X			X			X	
Density catchable wild trout			X											
10. Number of individuals (or catch per effort)	X	X	X	X	X	X ^c	X ^c		X	X	X ^c		X	
Density of individuals								X						X

FOR REFERENCE PURPOSES ONLY

Percent abundance of dominant species														X	X
Biomass (per m ²)															X ^e
11. Percent hybrids	X							X							
Percent introduced species				X		X									
Percent simple lithophills						X						X	X		X
No. simple lithophills species								X							
Percent native species						X									
Percent native wild individuals						X									
Percent silt-intolerant spawners														X	
12. Percent diseased individuals (deformities, eroded fins, lesions, and tumors)	X	X		X	X	X	X	X		X	X	X		X	X

Note: X = metric used in region. Many of these variations are applicable elsewhere.

^a Metric suggested by Moyle *et al.* (1986) or Hughes and Gammon (1987) as a provisional replacement metric in small western salmonid streams.

^b Non-coastal Plain streams only.

^c Boat sampling methods only (*i.e.*, larger streams/rivers).

^d Excluding individuals of tolerant species.

^e Coastal Plain streams only.

Source: M.T. Barbour, J. Gerritsen, B.D. Snyder, J.B. Stribling, *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, second ed., Report No. EPA 841-B-99-002, U.S. Environmental Protection Agency, Office of Water, Washington, DC, 1999.

The systematic biological exchange of materials between the organism, in this case various species of fishes, is known as uptake, which can be expressed by the following three differential equations for each age class or cohort of fish [43]:

$$\frac{dB_f}{dt} = J_g + J_i + J_{bt} \quad (8.3)$$

where J_g represents the net chemical exchange ($\mu\text{g d}^{-1}$) across the fish's gills from the water, J_i represents the net chemical exchange ($\mu\text{g d}^{-1}$) across the fish's intestine from food, and J_{bt} represents the compound's biotransformation rate ($\mu\text{g d}^{-1}$).

$$\frac{dW_d}{dt} = F_d - E_d - R - EX - SDA \quad (8.4)$$

where B_f = compound's body burden ($\mu\text{g fish}^{-1}$) and W_d = dry body weight ($\text{g dry wt fish}^{-1}$) of the average individual within the cohort; and N is the cohort's population density (fish ha^{-1}).

$$\frac{dN}{dt} = EM - NM - PM \quad (8.5)$$

where F_d = the fish's feeding, E_d = egestion (i.e., expulsion of undigested material), R = routine respiration, EX = excretion, and SDA = specific dynamic action (i.e., the respiratory expenditure in excess of R required to assimilate food). All of these parameters have units of g dry wt day^{-1} .

Physiologically based models for fish growth are often formulated in terms of energy content and flow (e.g., kcal fish^{-1} and kcal day^{-1}), Eq. 8.2 is basically the same as such bioenergetic models because energy densities of fish depend on their dry weight [44]. Obviously, feeding depends on the availability of suitable prey, so the mortality of the fish is a function of the individual feeding levels and population densities of its predators. Thus the fish's dietary exposure is directly related to the organism's feeding rate and the concentrations of chemicals in its prey.

The amount of any substance (e.g., nutrient, pollutant, or microbes) that is discharged into a system by point and nonpoint sources is known as the *load*. Chapters 13 and 33 discuss how the loading of nutrients, pollutants, and microorganisms can be quantified as to the gross mass of the substance entering an ecosystem and by the response of the ecosystem to the load. The means by which the loads enter an ecosystem vary. For example, as shown in Fig. 8.6, microbes can enter an aquatic system in various ways and with varying effects.

Loading calculations must take into account background sources (sometimes referred to as "natural" sources). Atmospheric loading is similar, but usually the distinctions are made between *mobile sources* and *stationary sources*. Two systems, hydrologic and atmospheric, join at the interfaces between earth and water bodies and the atmospheric, that is, terrestrial and tropospheric fluxes. For example, atmospheric deposition is an important source of nutrient loading (e.g., N, P, S, and K) to ecosystems. Ecosystems, for example, wetlands, load nutrients back into the atmosphere, but often as different chemical species. That is, the ecosystems are acting as control volumes in which reactions are taking place. Many of these reactions are biotic and are mediated by microbes and plants.

The linkages between biota and their environments are influenced by the availability and forms of nutrients. When rain containing nitrates falls to the wetland water and land surfaces, for instance, plant roots take it up and metabolize it into organic forms of nitrogen. Meanwhile, bacteria in sediments reduce it to ammonia. In the opposite direction, the reduced forms are oxidized by other bacteria (e.g., *Nitrosomonas* converts ammonium ions $[\text{NH}_4^+]$ to nitrite $[\text{NO}_2^-]$, *Nitrobacter* converts the NO_2^- to nitrate $[\text{NO}_3^-]$). Thus two opposite reactions are at play constantly in loading scenarios. In this instance, these are *ammonification* (or *deamination*) and *nitrification*:

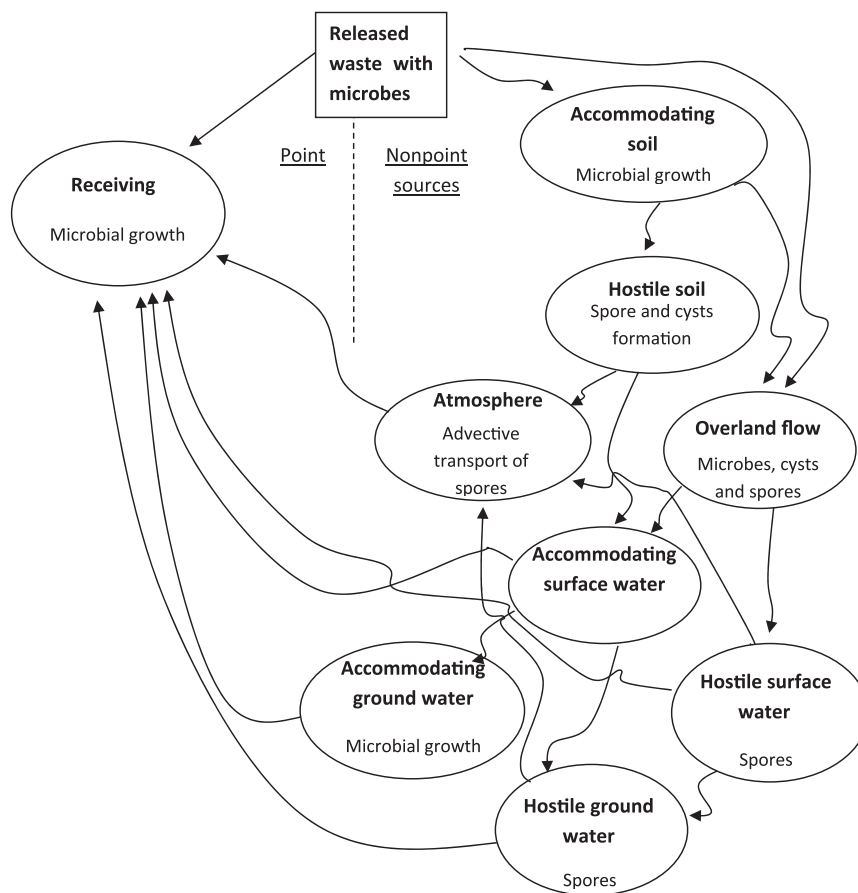
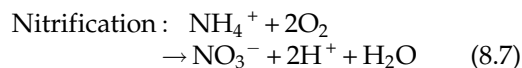
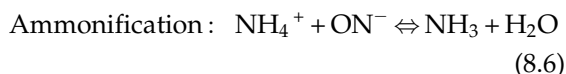


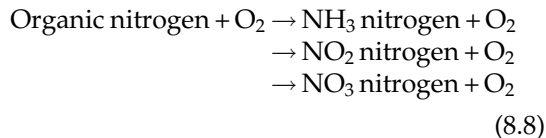
FIG. 8.6 Point source and nonpoint loading and impact of microbial populations. In a point source, the growth, metabolism, and formation of cysts and spores depend on the conditions of the receiving water body, which varies with time but not in space. In a nonpoint source scenario, the growth, metabolism, and formation of spores and cysts are a cascade in time and space. In accommodating environments, the microbes will undergo metabolism and growth, which may allow for larger microbial populations delivered to other compartments and eventually to the receiving body. However, various compartments in the flow may be hostile (insufficient nutrients, water, pH, temperature, etc.). These may induce the formation of spores which can be advectively transported in the atmosphere or by with the flow of ground and surface waters. *Source: D. Vallero, Environmental Biotechnology: A Biosystems Approach, Elsevier Science, 2015.*



Note that ammonification is written as an equilibrium reaction, and nitrification is a

kinetic (one-directional arrow) oxidation reaction. However, the loading depends on numerous environmental conditions, including pH. Thus under acidic conditions, most of the ammonia nitrogen will ionize to ammonium and under basic conditions the nonionized ammonia concentrations will increase in proportion to the ammonium. This is important

since nonionized ammonia is very toxic to aquatic biota, whereas ionized species are nutrients needed for plants and algae. Add to this, the decomposition of organic matter, and the loading becomes a complicated mix of reactions:



Even this is a gross oversimplification, since the oxidation and reduction depends on the types of bacteria present. For example, the O_2 required for nitrification is theoretically $4.56 \text{ mg O}_2 \text{ mg}^{-2} \text{ NH}_4^+$, but this is an *autotrophic* reaction. Thus O_2 is being produced by the nitrifying bacteria, decreasing the amount needed. However, the growth rate of nitrifying microbes is far less than that of *heterotrophic* microbes decomposing organic wastes. Therefore when large amounts of organic matter are being degraded, the nitrifiers' growth rate will be sharply limited by the heterotrophs, which means the rate of nitrification will commensurately be decreased [45]. Furthermore, these same responses to conditions exist for all other nutrients in the system, for example, organic P will be oxidized and oxidized P species reduced, etc. Thus the kinetics of nutrient loading are quite complex.

5.2 Stressor Loading

In the United States, the Clean Water Act (CWA) restricts the total maximum daily load (TMDL) of pollutants released to water bodies that have been deemed to be *impaired* by the state in which technology-based and other engineering controls are not adequate to achieve water quality standards. Thus the TMDL reflects the amount of a pollutant that can be discharged from point, nonpoint, and natural background sources, including a margin of safety (MOS) for any water quality-limited water body. The TMDL process consists of five steps:

1. Selection of the pollutant in need of consideration;
2. Estimation of the water body assimilative capacity (i.e., loading capacity);
3. Estimation of the pollutant loading from all sources to the water body;
4. Analysis of current pollutant load and determination of needed reductions to meet assimilative capacity; and,
5. Allocation, including a margin of safety, of the allowable pollutant load among the different pollutant sources in a manner that water quality standards are achieved.

A beneficial use that has been impaired is a function of a change in the chemical, physical, or biological integrity of surface waters, such as:

- restrictions on fish and wildlife consumption
- tainting of fish and wildlife flavor
- degradation of fish wildlife populations
- fish tumors or other deformities
- bird or animal deformities or reproduction problems
- degradation of benthos
- restrictions on dredging activities
- eutrophication or undesirable algae
- restrictions on drinking water consumption, or taste and odor problems
- beach closings
- degradation of esthetics
- added costs to agriculture or industry
- degradation of phytoplankton and zooplankton populations
- loss of fish and wildlife habitat.

The general components needed to develop a TMDL are shown in Fig. 8.7. Meeting water quality standards is a way to protect beneficial uses, including recreational activities, aquatic life, and water supply. For example, recreational beneficial use can be based on protection against fecal coliform, including *Escherichia coli* bacteriological criteria. For example, if a lake is designated for primary contact recreation water, potential exposures to bacteria and a baseline level of

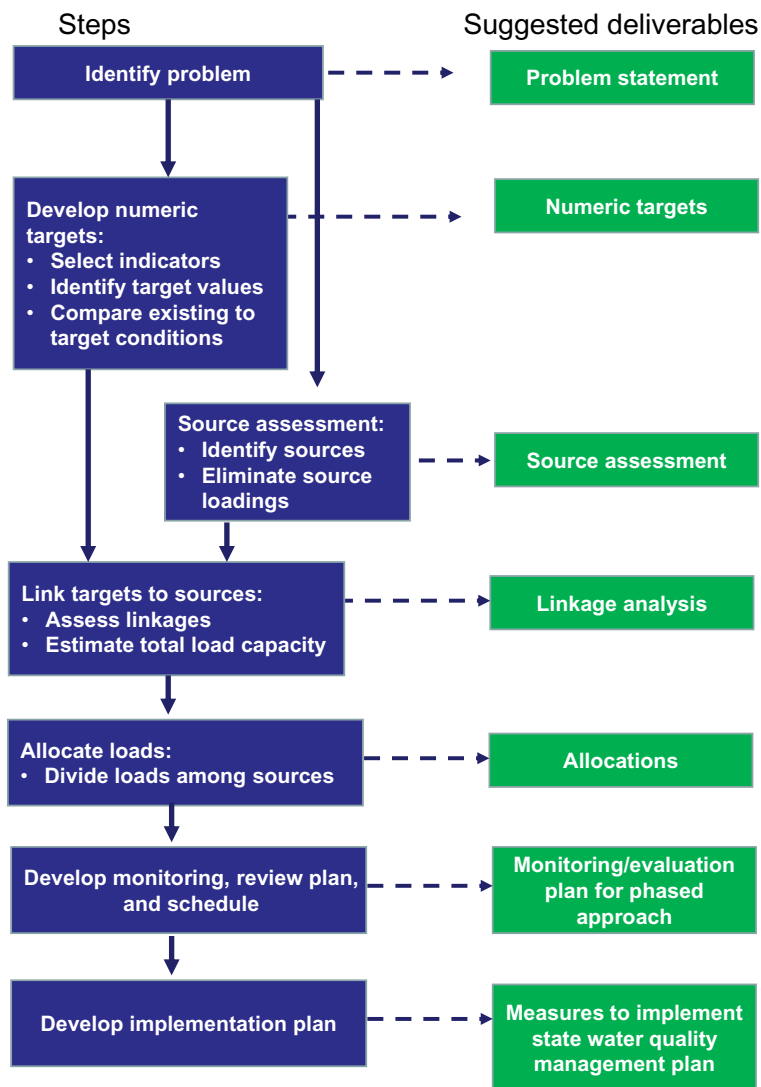


FIG. 8.7 Steps in developing a total maximum daily load. Source: [46].

disinfection will be required. This can be more straightforward for point sources, for example, building wastewater treatment systems, than for nonpoint sources. The latter often requires management approaches, such as measures to prevent soil erosion since soil may carry coliform bacteria.

6 HABITAT LOSS AND DESTRUCTION

The bulldozer can be a stressor or at least a tool that induces the stress. Changes to the landscape are an example of physical stress. Waste management plans must consider approaches



(A)



(B)

FIG. 8.8 Installation of sewer lines in Chatham County, North Carolina. The ecosystem disruption during construction is an example of a short-term stress on the lake and riparian ecosystems. The accessibility and attendant development will result in long-term and permanent changes that will lead to habitat loss and disruptions. Photos by author.

to minimize impacts of construction, development, and facility operation on the surrounding watershed, by preventing water pollution and actions that disrupt natural drainage patterns. In addition, waste managers must ensure their actions are consistent with local land use plans that directly address habitat destruction. This includes recommending ways that any development conserve land that serves as habitat for native flora and fauna, both on- and off-site, and directly and indirectly.

An example of indirect destruction or secondary impacts from infrastructure development is the location of new sewer lines or roads in previously undeveloped or low-density land (see Fig. 8.8). This invites new residential and commercial development, which in turn calls for more roads, structures, and impervious surfaces. These changes then lead to less soil infiltration and increase the risks of flooding on-site and downstream, as the holding capacity for water during rain events decreases.

It may not take much change to a landscape to lead to substantial adverse outcomes. A road can split a habitat in such a way as to truncate a migration route for mammals. A small change to a wetland decreases its acceptability as a migration stopover for migratory birds and as protection of prey from predators. These are both examples of changes to ecosystem function elicited by changes in ecosystem structure.

Scale is important. Ecosystems can be affected by the long-range transport of pollutants, acid rain, and climate change (see Fig. 8.9). However, most waste management decisions are made at the local level. However, the waste manager must take the view that local decisions combine to have larger, even global consequence. Thus actions taken need scrutiny from the standpoint that larger scale problems, for example, climate change, can be irreversible and that under many predicted scenarios would lead to widespread and severe damage to public health and ecosystems (the upper right-hand portion of Fig. 8.9). The ecological effects include loss of diversity and productivity [47, 48], and both direct and indirect effects on human health, for example, higher incidences of heat stroke and changes in epidemics [49].

6.1 Resilience, Diversity, Productivity and Sustainability

In addition to ecological risk and reliability, environmental systems scientists are increasingly emphasizing the importance of ecosystem resilience. Certain habitats are not particularly resilient, that is, making them vulnerable to adverse outcomes that are irreversible [50]. In this sense irreversibility is indirectly proportional to a system's resilience. A system with greater biological diversity is also usually more resilient than one with less diversity [51]. A monoculture plantation, for example, is not diverse, nor resilient, so it cannot withstand the insults posed by drought, insects, and so on. Thus habitats shown in the lower left-hand region of Fig. 8.10 would more likely endure

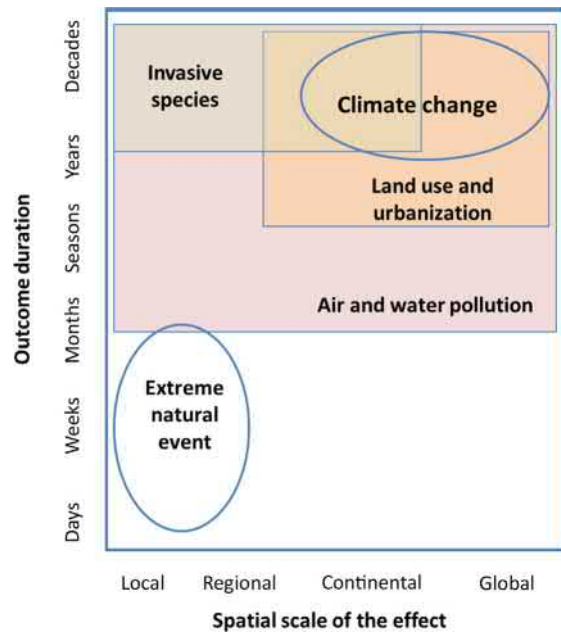


FIG. 8.9 The adverse outcome resulting from exposure to a stressor has temporal and spatial qualities. Local exposures to stressors can result from poor waste management decisions. At the other extreme, global climate change can result from chronic releases of greenhouse gases with expansive planetary impacts in direct proportion to significant changes in global climate (temperature increases in the troposphere and oceans, shifting biomes, sea level rise, and migratory patterns), the collective result waste management decisions worldwide. There are also instances where a local event can lead to spatially and temporally extensive outcomes, for example, meltdown at a nuclear power plant, releasing radioactive material that is transported long distances by winds aloft and ocean currents. *Sources: Based on the presentation by R. Araujo, U.S. Human and Ecologic Exposure Science: Divergence and Rapprochement, Environmental Protection Agency, 2007.*

irreversible harm from exposure to pollutants that damage habitat than those in upper right-hand region. Thus resilience should be a key factor when siting and operating a waste management facility.

Resilience is analogous to hysteresis in physics and engineering. A resilient organism or ecosystem can withstand a disturbance without

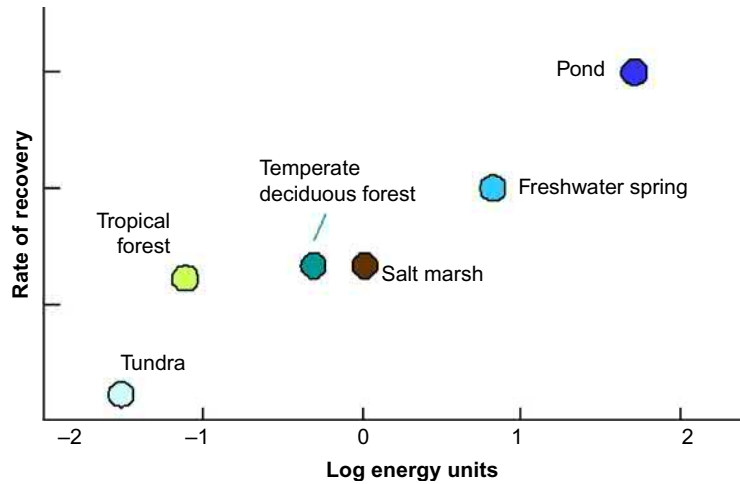


FIG. 8.10 System resilience index calculated from bioenergetics for six community types. Rate of recovery units are arbitrary; energy units = energy input per unit standing vegetation. Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*. Elsevier Science, 2015; data from: R. O'Neill, *Ecosystem persistence and heterotrophic regulation*, *Ecology*, 57(6) (1976) 1244–1253; M. Begon, J. Harper, C. Townsend, *Ecology: Individuals, Populations and Communities*, Blackwell Scientific, Boston, MA, 1996.

shifting to an alternative state and can continue to function as if the disturbance had not occurred [52]. Resilience can be described by the magnitude of disturbance that is needed before a state shift occurs [50, 53], for example, if a hypothetical tundra forest system loses 90% of its canopy species with a decrease of 5" rainfall per year, but a temperate forest loses none of its canopy species with the same rainfall decrease, the temperate forest is exhibiting resilience in its function and structure, at least for the drought stressor. The other metric of resilience is the rate of recovery. Consider two tundra forests that experience a decrease of 50% of their species abundance due to a drought-exacerbated insect infestation. The first does not regain the diversity in 5 years, but the second recovers in 2 years. Thus the second forest is more resilient.

Biodiversity determines an ecosystem's composition, structure, and function. Composition describes the organisms and their genetic makeup. Structure physical pattern of the system, for example, habitat complexity is indicated by the pattern of patches at a landscape

scale. Function is all of the "ecological and evolutionary processes and mechanisms" that take place in an ecosystem [54]. The diversity of a community in an aquatic or wetland ecosystem can be quantified, for example, by applying the Shannon–Weiner index:

$$D = -1.44 \sum_{i=1}^m P_i \log_2 P_i \quad (8.9)$$

or

$$D = -1.44 \sum_{i=1}^m (n_i/N) \ln(n_i/N) \quad (8.10)$$

where D = index of community diversity; $P_i = n_i/N$; n_i = number (i.e., density) of the i th genera or species; N = total number (i.e., density) of all organisms in the sample; $i = 1, 2, \dots, m$; and m = number of genera or species.

The larger the value of D , or community diversity, the greater is the stability of the ecosystem (see Example Box 8.1).

Productivity is an expression of how economical a system is with its energy. How much

BOX 8.1 ESTIMATING BIODIVERSITY

To understand biodiversity, consider the following hypothetical case [55].

An environmental assessment of microbes in a small stream near a landfill found a total of 1510 organisms, represented by seven different species. The actual number count of each microbial species in stream community was 10, 50, 75, 125, 200, 350, 750 mL^{-1} .

Solution and Discussion:

Construct a table to derive the values needed to find D , using Eq. 8.9:

$$D = -1.44 \sum_{i=1}^m (n_i/N) \ln(n_i/N)$$

i	n_i	n_i/N	$-1.44 \ln(n_i/N)$	$-1.44 \ln(n_i/N)$
1	10	0.006623	7.224883	0.047847
2	50	0.033113	4.907292	0.162493
3	75	0.049669	4.323423	0.21474
4	125	0.082781	3.587834	0.297006
5	200	0.13245	2.911028	0.385567
6	350	0.231788	2.105182	0.487956
7	700	0.463576	1.10705	0.513202
Σ	1510	1		2.10881

Thus the diversity index is approximately 2.1. The index is most useful when comparing systems. So, if the stream is 2.1 and surrounding streams are all around 4, there may be a problem. For example, further investigation is needed if these are biological indicators of the health of the stream and the facility is emitting pollutants that are known to stress ecosystems. Generally, D values range from about 1.5 to 4.5.

A new leachate collection system is installed around the landfill, with measurements taken a year later with the following results, from which another index is calculated.

Construct a new table with four times each species:

i	n_i	n_i/N	$-1.44 \ln(n_i/N)$	$-1.44 \ln(n_i/N)$
1	40	0.006623	7.224883	0.047847
2	200	0.033113	4.907292	0.162493
3	300	0.049669	4.323423	0.21474
4	500	0.082781	3.587834	0.297006
5	800	0.13245	2.911028	0.385567
6	1400	0.231788	2.105182	0.487956
7	2800	0.463576	1.10705	0.513202
Σ	6040	1		2.10881

Even though the species abundance quadrupled, the index remains 2.1. The index indicates, correctly, that the total species abundance does not affect diversity.

Some new pollution sources are located near the ecosystem, so a follow-up study is conducted five years later, which indicates the species density has changed to 3000, 50, 35, 40, 30, 70, and 15 L^{-1} of the same species of microbes as the early study. How had the numbers and diversity changed in five years?

Again, calculate D by constructing a new table:

i	n_i	n_i/N	$-1.44 \ln(n_i/N)$	$-1.44 \ln(n_i/N)$
1	3000	0.92593	0.11082	0.10261
2	50	0.01543	6.00668	0.0927
3	35	0.0108	6.52029	0.07044
4	40	0.01235	6.32801	0.07812
5	30	0.00926	6.74227	0.06243
6	70	0.0216	5.52216	0.11931
7	15	0.00463	7.7404	0.03584
Σ	3240	1		0.56144

After 5 years, the actual number of microbes is more than doubling, but the diversity has been drastically reduced ($D = 0.6$ vs. 2.1). This may indicate that conditions favorable to one species,

Continued

BOX 8.1 ESTIMATING BIODIVERSITY (*cont'd*)

for example, the presence of a toxic chemical or a change in habitat (e.g., a road to the landfill), are detrimental to the other six species.

A follow-up question must be asked. Were the assessments conducted in the same season (some microbes grow better in warmer conditions, while others may compete more effectively in cooler waters)? If the studies are comparable,

further investigation is needed, but this certainly is an indication that things are amiss, since Shannon values usually range from about 1.5 to 4.5. Diversity, like productivity, is often an important indicator of change. If diversity as measured by the index shows a decline, it may well indicate that an ecosystem is under increasing stress.

biomass is produced from abiotic (e.g., nutrients and minerals) and biotic resources (from microbial populations to canopy plant species to top predator fauna). One common measure is "net primary productivity" which is the difference between two energy rates:

$$P_1 = k_p - k_e \quad (8.11)$$

where P_1 = net primary productivity; k_p = rate of chemical energy storage by primary producers; and k_e = rate at which the producers use energy, for example, microbial respiration.

Sustainability describes the likelihood that the diversity and productivity will last. Even though an ecosystem appears to be diverse and highly productive is there something looming that threatens the continuation of these conditions? For example, is an essential nutrient being leached out of the soil, or are atmospheric conditions changing that may threaten a key species of animal, plant, or microbe? Sustainability is difficult to quantify precisely.

Ecological risk assessments may be prospective or retrospective, but often are both. The Florida Everglades provides an example of an integrated risk approach. The population of panthers, a top terrestrial carnivore in Southern Florida, was found to contain elevated concentrations of mercury (Hg) in the 1990s. This was observed through retrospective eco-epidemiological

studies. The findings were also used as scientists recommended possible measures to reduce Hg concentrations in sediment and water in Florida. Prospective risk assessments can help to estimate expected declines in Hg in panthers and other organisms in the food chain from a mass balance perspective. As the Hg mass entering the environment through the air, water, and soil is decreased, this should be compared to the concomitant reduction in the risk to sensitive species. Integrated retrospective prospective risk assessments are employed where ecosystems have a history of previous impacts and the potential for future effects from a wide range of stressors, which may be the case for waste operations, for example, hazardous waste sites.

7 CONCLUSIONS

The integrity of ecosystems is adversely affected by various physical, chemical, and biological stressors. Ecosystem risks, reliability, and resilience must be analyzed as waste managers decide on the best options for solid wastes. There are numerous tools, including indices and models, that are available to estimate the risk to ecosystems from waste management engineered systems that can complement other reliability metrics.

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Oil and Gas Exploration and Production Wastes

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1 INTRODUCTION

Fossil fuels have been the energy source of choice in most of the world since early in the 20th century. The specific types of fuel have been determined by the demands. For example, most motor vehicles have been fueled by gasoline or diesel fuel, with a small change in recent years to alternative fuels, such as biodiesel. The growing demand for electric vehicles is still heavily dependent on fossil fuels, given that a large percentage of electricity is generated by coal- and natural-gas fired electric generating facilities, with much of the rest from nuclear power plants.

Ironically, environmental concerns are among the reasons for increasing natural gas extraction. Natural gas combustion emits far less air pollutants than most other fossil fuels. The U.S. Department of Energy's National Energy Technology Laboratory (NETL) recently completed a study that found that natural gas generates substantially lower emissions of most air pollutants, including greenhouse gases, when compared to even efficient coal-fired facilities [1]. The demand for natural gas is also attractive to the United States in its efforts to reduce its dependence on crude oil imported from other countries.

2 LIFE CYCLE PERSPECTIVES

Optimizing and selecting the best process, including the type of fuel, requires a systems approach. An increasingly useful tool in this regard is the life cycle assessment (LCA; see [Chapter 2](#)). One of the key requirements is that energy production and use be sustainable, assuring that not only a level of air quality be met continuously for the foreseeable future, but all environmental values are sustained [2]. This begins even before extracting the fuel source and must account for energy, labor, and other aspects of a project before extraction from the earth, manufacture, operating life, and end of life (including disposal and recycling). The LCA must consider values beyond its utility at hand. In addition to the scientific assessment of human health and ecosystem risks, the LCA must consider the wastes generated in a way that protects the fabric of the community, including the vitality, history, and connections within the neighborhood and the other neighborhoods to which it is connected [3].

2.1 Process Change

An example of this decision faced by plant managers and other decision makers is whether to change a process. This certainly can be involved in selecting the best way to produce energy, but it may also include most other industrial and waste management decisions where thermal processes are involved.

Consider the choice of whether to burn 100L fuel A to manufacture 1000kg of product Y using a process that releases 100kg of SO₂ per year versus burning 150L of fuel B to manufacture the same amount of product Z, but releasing 300kg of SO₂ per year. If this were the only criterion, fuel A would unquestionably be the best choice. It is more energy efficient, that is, uses 50% less fuel, and releases one-third of the air pollutants. However, earlier in the life cycle fuel A requires that 1 metric tonne (t) of

earth is removed to produce the 100L of fuel A, but fuel B requires no extraction, since the fuel is generated from recycled food oils, for example, biodiesel. In the earliest stages of the life cycle, fuel A results in more environmental harm than does fuel B. It could be that the extraction process does not emit a large amount of air pollutants, although they usually do in the form of fugitive dust (particulate matter), but they are likely to damage ecosystems, soils, and water systems. Furthermore, the two fuels will have different costs and benefits at the other levels.

In the event that the fuel decision is driven by upstream effects, for example, extraction of ore, which have overridden downstream effects, for example, air emissions, this is further complicated by the so-called end-of-life stage of the life cycle. For example, the solid wastes generated from the very pollution control actions could be a headache for the waste manager. The SO₂ removal may be accomplished by limestone scrubbers. Increasing the efficiency of SO₂ removal directly increases the amount of waste generated. The dewatering and other disposability factors drive up costs and may increase the risk of migration from waste storage areas to water supplies and cause other environmental impacts [4]. Thus fuel choice and process change decisions must be considered from multicompartmental perspectives. In this case, the end-of-life stage detracts from choosing a high-sulfur coal, compared to crude oil and, especially, natural gas. In addition, both of the latter usually produce much less ash, which also is a great advantage to waste management (see [Chapter 7](#)).

The plant and waste managers may apply the payback ratio (E_{pr}), that is, the ratio of total costs, mass, or energy produced during a system's normal lifespan, divided by the costs, mass, or energy needed to build, install, maintain, and operate that system. It can also be expressed as the energy generated (E_g) per energy consumed (E_c):

$$E_{pr} = \frac{E_g}{E_c} \quad (9.1)$$

For example, if a natural gas power plant consumes 3.0×10^6 gigajoules (GJ) to generate 1.2×10^7 GJ and a larger coal-fired plant consumes 9.5×10^7 to generate 1.0×10^9 GJ, their payback ratios are:

$$\text{Gag} : E_{pr} = \frac{1.2 \times 10^7}{3 \times 10^6} = 4 : 1$$

$$\text{Coal} : E_{pr} = \frac{1.0 \times 10^9}{9.5 \times 10^7} \approx 11 : 1$$

A high ratio indicates good environmental performance or effectiveness. From a purely caloric perspective, the coal-fired plant has a much better payback ratio. However, this does not account for waste handling and other pollution control costs, in addition to costs and risks that are difficult to monetize, such as reduced visibility from haze, damage to crops for air pollution, and the need to handle sludge and other wastes.

Some of these other costs can be addressed by using “energy return on the energy investment” (EROEI). According to the second law of thermodynamics, energy production cannot be 100% efficient, given the energy losses with each conversion. For instance, the chemical energy of crude oil well is diminished during extraction, processing, and transport on its way to the end use and is further diminished by losses at the end use, for example, inefficiencies within the internal combustion engine. The EROEI the ratio of the energy obtained from the resource to the energy expended in production, but is actually an enhancement of the expression of net energy, that is, the energy produced minus the energy expended. Thus an $\text{EROEI} \leq 1$ means that the net energy ≤ 0 . Thus the problems with ethanol mentioned before can be expressed as an EROEI. Arguably, for corn-based ethanol production, if the fossil fuel life cycles are included in the calculation, EROEI is lower than if this is calculated later in the life cycle, since farming and handling of corn is very fossil-fuel dependent. Thus ethanol’s EROEI can be substantially improved with a whole-plant type method

versus the fruit-only fermentation process. The EROEI is also a useful tool for comparing stationary and mobile sources. For example, one could describe electric cars as being either nuclear or coal-fired vehicles, since most electricity is generated from these two stationary source types. Thus the life cycles of an electric versus gasoline fueled vehicle could be compared using the EROEI.

Process and fuel change often include numerous options, each with its own cross-over and combinations of process change options with their own collective cross-over. Sometimes, combining options is synergistic. That is one option may be to use less toxic raw materials and another option may be to change to operating temperature in reactor to decrease the generation of a caustic and toxic substance. However, the combination of these two options may not only lead to the elimination of the substance in the gas stream, but may greatly increase the efficiency of fabric filters downstream, as well as extend the time needed for cleaning and replacement. This is not only beneficial financially, but could greatly lower the amount of particulate matter (PM) released. Each filter cleaning and/or replacement is followed by an increase in PM until the dust cake is formed. Thus the combined process option changes could obviate the need to add pollution control equipment for the caustic pollutant, improve filtration efficiency, and reduce PM emissions.

Conversely, some option combinations can be antagonistic. Solving a problem in one part of the system, for example, installing complicated and expensive waste control technologies, with high operation and maintenance (O&M) needs, could introduce problems downstream if the line is shut down too often. Another example would be to add a sorbent to improve an upstream technology that generates particles with low electrical conductance, thus interfering with and lowering efficiencies of electrostatic precipitators downstream. Thus when evaluating and considering process change options, it

is important to consider the systematic effects of each option and the combinations of various options.

The chemistry and physics are also well understood. Good industrial practice minimizes the “black boxes” of a process; otherwise adjustments in production and output of products would be very risky (i.e., a catalyst concentration may have a very tight tolerance range, outside of which the process does not work well or at all). Finally, the loss term in the mass balances is well understood. If (raw material A) + (raw material B) – (losses of A and B) = (Product C – losses), the plant manager needs precise and accurate data on these loss terms. These data document what leaves the process through vents, stacks, pipes, and other conveyances, as well as via fugitive emissions. Many of these losses are indeed air pollutants.

Other improvements include change to a less polluting fuel. For example, if a power plant emits large quantities of SO₂ and fly ash, conversion to natural gas may be much less expensive than installing the necessary control equipment to reduce the pollutant emissions to the permitted values. If the drier at an asphalt plant was emitting 350 mg of particulate matter per standard cubic meter of effluent when fired with heavy oil of 4% ash, it was probable that a switch to either oil of a lower ash content or natural gas would allow the operation to meet an emission standard of 250 mg m⁻³.

Pollution prevention has the distinct advantage over air emission controls in that the company not only eliminates or greatly reduces the release of pollutants, but it also saves money. Direct costs include labor, raw materials, energy use, capital equipment, site preparation, tie-ins, employee training, and regulatory recordkeeping (e.g., permits). In addition, there are indirect cost savings, for example, time saved from submitting compliance permits and suffering potential fines for noncompliance. The added, yet often intangible, benefit to the waste manager is that removing a hazardous substance or

dangerous situation from a process for environmental reasons can also lead to a cleaner work environment and decreased occupational risks.

The LCA aids in selecting a process that provides the desired function, with the least amount of damage and the greatest reward. Too often, waste management decisions related to fuel choice have been treated as separate processes, as opposed to being part of a comprehensive life cycle perspective. Upstream, mining impacts have not necessarily been connected to decisions about the best way to address emissions from the refinery or the power plant. Often different agencies issue permits and licenses for mining and the refining operations. The same is true for distributors of ores, crude oil, and fuel. Pipelines are regulated differently than rail, which has different requirement than trucks. Finally, operators and users of the fuel are regulated separately and differently than those who provide the fuel. Not only is the system segmented among air, water, and other environmental media, but it is segmented within the air medium.

Most environmental laws and regulations address a single compartment, with separate statutes designed to protect air, water, and land, which are different from solid and hazardous waste laws. Within this framework, the waste manager must view oil, gas, and other fuel needs systematically, even in light of this diverse regulatory framework.

3 TRADITIONAL OIL AND GAS EXTRACTION

Pulling fluids out of the ground requires a pressure differential. To reach the earth's surface, the pressure in the fluid reservoir must be higher than the pressure at the surface. When the reservoir is hundreds of meters below the surface, piping and other conveyances must be installed. The longer the distance and the smaller the pressure differential, the greater will be

the engineering challenge. Such conveyance, for example, must minimize leakage. This is both an engineering and environmental challenge. Leakage means loss of pressure, so the engineered system employed must add additional pressure to maintain sufficient pumping pressure differential to pull the fluid to the surface. When a casing leaks, it may migrate to other aquifers, including those needed to provide drinking water.

3.1 Oil Spills

Any large oil or gas extraction and transport effort threatens the environment. Ecosystems can be adversely impacted by the leakage of fluids, but also by the extraction activities, for example, noise, physical barriers and disruptions, and other stresses (see [Chapter 8](#)). If the extraction occurs on or near the ocean, spills are possible.

The number of crude oil spills increased with the increase in transport distance (see [Table 9.1](#)). The largest spill at sea in terms of amount of

release occurred in 1979 when the Atlantic Empress spill 287,000 t of crude oil near Tobago in the West Indies. Oil spills result from many causes. Arguably, the Exxon Valdez was the most notorious spill prior to the Deepwater Horizon spill in the Gulf of Mexico. However, the Valdez stands at in 35th position in terms of weight (37,000 t). Thus quantity of spill, or other waste products, is but one of the public's criteria of damage. In the case of the Valdez, the sensitivity of the habitat was weighted heavily.

The causes of spills vary widely, but there appears to be a difference between very large and smaller spills. Equipment and hull failures account for nearly half (46%) of all spills. The difference seems to lie in where the spills occur. Most large spills occur in open water, whereas for the smaller spills (<7 t) have occurred most often near coasts, with most in the port, for example, loading and discharging the fluid.

Increasingly, extraction site has been the site of the spill. This is because new methods have to be used to extract oil and gas in very deep

TABLE 9.1 Largest Oil Spills Since 1967, Ranked by Weight of Product Spilled

	Operations						
	At Anchor (Inland/ Restricted) 13	At Anchor (Open Water) 9	Underway (Inland/ Restricted) 82	Underway (Open Water) 225	Loading/ Discharging 41	Bunkering 1	Other Operations/ Unknown 83
<i>Causes</i>							
Allisions/collisions	6	5	33	65	1	0	24
Groundings	4	2	45	66	2	0	29
Hull failures	0	1	0	50	0	0	8
Equipment failures	0	0	0	7	11	0	1
Fires/explosions	1	1	3	25	14	1	9
Other/unknown	2	0	1	12	13	0	12
Total	13	9	82	225	41	1	83

Source: International Tanker Oil Owners Pollution Federation, Limited (2012). Statistics. <http://www.itopf.com/information-services/data-and-statistics/statistics> (accessed 14.03.12).

waters, where a foundation for a derrick is not possible. This is often accomplished by dynamic positioning, that is, the platform is held in place by active systems. The Deepwater Horizon

extraction of oil from the Macondo well in the Gulf of Mexico provides an example of this method and the risks from offshore drilling (see [Discussion Box 9.1](#)).

DISCUSSION BOX 9.1 DEEPWATER HORIZON SPILL [5–8]

The Deepwater Horizon (see [Fig. 9.1](#)) was a dynamically positioned, semisubmersible offshore oil drilling rig, designed to drill in ultra-deep waters. Dynamic positioning means that the vessel is kept in place using computerized thrusters and propellers.

In the early morning of April 18, 2010, the Deepwater Horizon drill crew began lowering the long-string production casing. Six centralizers had already been installed on the lower 7-in. interval of the production casing string, which was significantly less than called for by cementing models. Such models recommended larger numbers of centralizers in order to reduce the reasonable risk of cement channeling and subsequent gas flow. The drill crew completed running the production casing on April 19, 2010. Casing is typically installed with two sets of cementing check valves: the float shoe, located on the very bottom of the casing string; and the float collar, usually installed from two to six casing joints above the bottom. BP's production casing design

for the Macondo well called for only one cementing check device, consisting of a double valve and an auto-fill float collar.

Lowering the casing string into the well with the float equipment installed pushes drilling fluid ahead of it and can create surge pressures that can fracture the formation, leading to loss of drilling fluids and damage of the hydrocarbon production zones. To reduce surge pressure and protect the formation, the well owner, BP, had incorporated a surge reduction system including an auto-fill type of float collar and reamer shoe. The float collar used at Macondo contained two flapper check valves that are held open during installation by an auto-fill tube. While open, these valves allow mud to pass through the float collar and up into the casing. Before cementing, the float collar is “converted” or closed. Specifically, the auto-fill tube is forced out of the float collar so that the flapper valves close and prevent mud and cement slurry from flowing back up into the casing.



FIG. 9.1 Deepwater Horizon drilling rig in flames. U.S. Coast Guard photo.

DISCUSSION BOX 9.1 DEEPWATER HORIZON SPILL (*cont'd*)

The window for safe drilling between the fracture gradient and the pore-pressure gradient decreased as the drilling became deeper. It became increasingly difficult to keep the right amount of equivalent circulating density, so that perturbances and fluid losses increased. As this safety window narrowed, BP began to change plans by reducing the well's target depth, considering changes in well casings, reducing the circulating rate below the parameters specified to convert the float collar, decreasing the density of cement with nitrogen foam, using less cement, and ceasing to conduct complete bottoms-up cementing. While these actions may have protected the formation and allowed operations to continue, they contributed to the disastrous spill.

In addition, the initial displacement was not properly planned and executed. A negative pressure test was needed to make certain that the cement would stop flowing from the oil reservoir into the well after seawater replaced the drilling mud. The test should have been a red flag of trouble ahead, that is, the pressure readings on the drill pipe were abnormal. This should have been a warning that the cement barrier was not working. Pressure was bypassing the cement and float equipment, so that the well was still connected to the oil formation. At the very least, this was a miscalculation, since the negative pressure test results were misinterpreted. The failure was compounded when BP decided to go ahead with the final displacement.

The BP oil spill flowed into the Gulf for 3 months and is the largest oil spill disaster in the history of the oil industry. The explosion on the rig killed 11 men and injured 17. The oil poured out of a leak on the seafloor bottom. It released 780,000 m³ (4.9 million barrels) of oil into the Gulf of Mexico, and about 500 miles of

Louisiana, Mississippi, Florida, and Alabama coastline was contaminated by BP oil. The spill affected every type of flora and fauna in the area, whales and dolphins died at twice their normal rate, wetland grass and flora died and fishing came to a halt, and an underwater plume, not visible on the surface killed seafloor flora and fauna, BP admitted that it made mistakes and soon after the accident set up a \$20 billion fund to compensate victims of the oil spill. Strong efforts of public agencies and private concerns were made to reduce the impact of the oil and to collect as much as possible. Skimmers were used, detergents sprayed on the oil, and controlled burning took place.

Approximately 30%–40% of the spilled crude was estimated to remain in the Gulf within a year of the spill, but this is highly uncertain since the extent and degree of biodegradation is not known. A study of about 3000 Gulf of Mexico sediment samples 4 years after the spill found that the rate at which the crude oil is breaking down is typically faster in the water than in the sediment, that is, suspended oil particles compared to rates after reaching the floor [9]. Other factors, such as oil droplet size and temperature, affect degradation rates of spilled oil [10].

As is often the case in large-scale environmental disasters, many of the effects are not evident until months and years later. In addition to the exposures to crude oil, some of the very products used to contain and remove the wastes, that is, the dispersants, appear to have exacerbated the health effects that appeared later.

The Deepwater Horizon Oil Spill Coast Guard Cohort study of 8696 responders found statistically significant increases in several health problems, including lung irritation, rashes, and gastrointestinal problems [11].

3.2 Small-Scale Oil and Gas Problems

Waste managers are much more likely to respond spills onto land from oil and gas operations than to spills into oceans and large bodies of water. A pipeline crack or leaking pump can be undetected for months or can immediately release millions of liters of oil. A gas line leak can contaminate the air, but can also lead to an explosion that can damage life and property. Indeed, the wastes from extracting oil and gas may build up above and below ground, ultimately requiring environmental remediation.

Most of the wastes from crude oil and natural gas exploration and production (E&P wastes) are subject to regulation of nonhazardous solid waste regulations in the United States and its states. Although the waste manager must be aware of the particular state regulations and guidance for E&P wastes. Some states continue to pass legislation and regulations, especially related to hydraulic fracturing, including waste management rules.

Generally, drilling wastes are in the form of the brine solution, "formation water." Oil extraction is made possible by pumping a mixture of oil, gas, and formation water from the underground reservoir to the surface. This solution is then separated from the oil and gas in tanks or pits, which results in so-called produced water. Most of the solution that is pumped to the surface is formation water. The percentage of oil or gas continues to decline in the formation water. With time oil and gas fields are predominantly left with produced water. Traditionally, production water was allowed to evaporate in large ponds on-site. This practice has decreased substantially the precipitate and dramatically concentrates whatever pollutants exist in the production water. Environmental concerns include contamination of aquifers, harm to wildlife, and esthetics. To address this, the production water has been reinjected into the reservoir, treated, or reused in applications in which the concentrations are not considered harmful.

Direct injection is a common method for storage of fluids, not just produced water. Direct injection has also been used for enhanced recovery of oil, that is, to increase pressure and volume of fluids in the reservoir to continue to extract oil. Enhanced recovery includes the injection of viscous fluids, gases, or heated water. Direct injection has also been used to move oil and gas into geologic formations for storage, for example, the Strategic Petroleum Reserve in the United States and natural gas storage in Mexico. These approaches have similar problems and risks to those associated with the original extraction activities, including contaminating water-laden aquifers. In the United States the underground injection program (UIC) classifies wells into six types [12]:

- I. Injection of hazardous wastes, as defined by the Resource Conservation and Recovery Act;
- II. Injection of fluids associated with oil and gas production;
- III. Injection of fluids to dissolve and extract minerals;
- IV. Shallow wells for injection of hazardous or radioactive wastes;
- V. Injection of nonhazardous fluids, often for injection of wastes into or above drinking water aquifers; and,
- VI. Injection of carbon dioxide into geologic formation for carbon sequestration.

The UIC program is mainly designed to protect drinking water supplies. The rationale is to prevent "endangerment," under Section 144.12 of 40 Code of Federal Regulations, "Prohibition of movement of fluid into underground sources of drinking water," which stipulates [13]:

No owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 CFR part 142 or may otherwise adversely affect the health of persons.

Class II wells inject and gas produced water. As mentioned, much of the waste is considered “nonhazardous,” but this is more of a regulatory than a health-based term. Obviously, the water contains hydrocarbons from the oil and gas, but also contains substances, some toxic, from the geological formation that have been concentrated by the extraction process. For example, naturally occurring radioactive material is known to exist in produced water and other wastes. Extraction activities concentrate these wastes, known as “technically enhanced naturally occurring radioactive material” (TENORM). Radium (Ra), uranium (U), thorium (Th), potassium (K), and their radioactive decay products have been found in oil and gas TENORM [14–16].

One of the important tools for determining the likelihood that a well will contaminate other aquifers is the mechanical integrity test (MIT). The MIT is conducted to determine the amount of leakage in the components of wells [17, 18], including the casing, packer, and tubing, as well as to determine if fluid is migrating to any location between the surface and the oil or gas reservoir, for example, via vertical channels adjacent to the borehole. If no leaks are detected in the casing, tubing, or packer, the MIT includes a tubing-casing annulus pressure test, time run method, or a tracer survey. If these are negative, further methods will be needed to ensure continued integrity, including the cement bond log.

3.3 Well Integrity Breach

Various factors can lead to the loss of integrity of an oil or gas well. One key factor is the cementing process. Cement is the means by which the wellbore is isolated and held in place to avoid casing failure to and prevent contamination of aquifers through which the wellbore traverses. Cementing is dependent upon [19]:

- Condition of drilling fluid;
- Use of spaces and flushes;
- Rotation and reciprocating of casings;
- Centralizing of casings;

- Maximization of displacement rate;
- Matching slurry to temperature;
- Selecting and testing cement formulations; and,
- Selecting the optimal cementing system.

In addition to cement, failure can result from a breach in any type of barrier, including the casing, liners, wellhead assemblages, geological barriers, and mechanical sealing devices, for example, packers. Furthermore, failure of oil and gas wells can result from inaccurate estimates of stimulation loads, that is, treatment and flowback; improper casing size; not fully accounting for oil, gas, and other fluid’s properties, for example, corrosiveness; and improper isolation and barriers [20]. Thus all potential flow paths must be known, even those that are unlikely, but which could contaminate aquifers or cause other problems.

Various means exist for ensuring that the geology is conducive to safe drilling. In particular, the waste manager should request information about the mechanical tests conducted, log analyses, pressure testing, microseismic testing, and tracer tests.

This means that when environmental problems arise, the waste manager must determine which of these or other factors may have contributed. Preferably, the waste manager could help to prevent these problems by identifying weaknesses in any operation within the jurisdiction. For example, questions or complaints from citizens may be early warnings of possible problems.

4 HYDRAULIC FRACTURING WASTES

Most of the waste management challenges associated with traditional oil and gas wells apply to the new methods of extraction. Arguably the most visible in recent years is hydraulic fracturing or “fracking.” The process is not new to petroleum engineering. The mechanical principles were well documented in the 20th century

[21, 22], for example, with methods dating back to the early 1920s and 1930s, with experiments conducted to replicate conditions of in situ stresses in rock formations [23] and capillarity mechanisms [24]. This approach has been enhanced in recent years to induce fracturing an oil- or gas-laden formation to stimulate the flow of natural gas or oil. In addition to traditional enhanced recovery of formally depleted wells, hydraulic fracturing may be applied to virgin rock formations in which oil and gas were known to exist, but which extraction was considered infeasible given the low oil or gas concentrations and/or formations that were previously inaccessible.

In hydraulic fracturing, wells may be drilled vertically deep below the land surface, but may also use horizontal or directional sections extending thousands of meters. The fractures result after pumping large quantities of fluids at high pressure down the wellbore into the rock formation, for example, shales. The fracturing fluid consists of water, chemical additives, and particles, known as proppants. The injected fluid opens and extends the rock fractures, often several hundred meters from the wellbore. The proppants be sand, ceramic pellets, or other incompressible particles, which keep the newly created fractures open.

After this injection process, the internal pressure of the rock formation is higher than that of the fractures, so the fluids return to the surface through the wellbore. This “flowback” of produced water likely will contain both the injected chemicals and materials from the formation, for example, TENORM. The flowback is commonly stored on-site in tanks or pits before being treated, disposed, or recycled. As is the case of traditional oil and gas recovery, the flowback is often injected underground for disposal.

The waste manager’s knowledge of hydraulic fracturing is especially critical in areas where it is already being or is contemplated to be applied. Hydraulic fracturing activities can impact the environment and public health in numerous ways, in varying levels of severity, including [25]:

- Reducing water availability, particularly in areas with limited or declining groundwater resources;
- Spills during the handling of hydraulic fracturing fluids and chemicals or produced water that result in large volumes or high concentrations of chemicals reaching groundwater resources;
- Injection of hydraulic fracturing fluids into wells with inadequate mechanical integrity, allowing gases or liquids to migrate to aquifers, including drinking water sources;
- Injection of hydraulic fracturing fluids directly into aquifers;
- Discharge of untreated or improperly treated wastewater to surface water; and
- Disposal or storage of hydraulic fracturing wastewater in unlined pits resulting in contamination of groundwater resources.

In addition, solid wastes generated by various steps will likely contain contaminants, including elevated concentrations of potentially toxic metals, hydrocarbons, and radioactive isotopes. These wastes must be handled properly, including adherence to hazardous waste storage and transportation rules, which vary by jurisdiction.

5 CONCLUSIONS

The waste manager is challenged to consider the life cycles of wastes generated by oil and gas production, whether traditional or novel. The dependence on fossil fuels will continue into the foreseeable future, as will the generation of these wastes. The rules that apply to oil and gas production and waste handling vary by type of operation and the characteristics of the waste product. In addition, nations and local jurisdictions often enforce differing rules, which requires that the waste manager be familiar with and adhere to what may be widely ranging regulations and standards.

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Metal Waste

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1 INTRODUCTION

The reuse of secondary metals constitutes the oldest and most important kind of recycling activity in the history of humankind. The recycling of metal dates back to approximately 10,000 years ago, and the main reason why metals have always been recycled is because of the large amount of energy that must be expended to extract a metal from its ores in the first place. This has not changed over the millennia. Steel and nonferrous metal industries are

among those sectors with the highest energy intensities and recycling saves up to 95% of the energy consumption expended in the production of the primary metal. Thus scrap and metal-bearing residues are of great importance when considering the purchase of raw materials to produce virgin metal. This is especially important for those countries which have little or no ore deposits. For instance in Europe, in the field of end-of-life vehicles (ELVs) and waste from electric and electronic equipment (WEEE), the EU directives created additional incentives

concerning metal reclamation and recycling. As WEEE also contains valuable material besides metals, Chapter 25 is dedicated to the recycling of this special waste stream.

In this chapter, the fundamentals of metal recycling are described. The mechanical processing of recycling scrap metal is a major focus of this chapter as these processes are all that is required in order to produce metals which can be utilized without any difficulties and without further treatment in metallurgical plants. These metallurgical processes include the machinery which is part of the downstream equipment involved in smelting and refining and thus these processes complete the recycling loop for metals.

2 SCRAP METALS

Metals for recycling include those that are recovered from large bulky equipment and often consist of both ferrous and nonferrous materials. The metals involved are mainly iron, steel, stainless steel (also called inox-steel), and several nonferrous (NF) metals. In this section the advantages and approximate quantities of metals recovered for recycling are discussed.

2.1 Ferrous Metals

In 2012 the total world steel production amounted to 1.5×10^9 t (1.5 billion tonnes) of which 0.57×10^9 t were fabricated from discarded metal waste. Thus roughly 37% of the world's steel output originates from scrap iron and steel. The energy saved from using recycled steel scrap amounts to approx. 75% of the energy that would have been spent to generate the steel from primary mineral raw materials and the CO₂ emissions are reduced by 58%. Furthermore, the recycling process results in an 86% reduction in air pollutants and a 97% reduction in mining waste [1].

Stainless steel is an iron alloy containing nickel, chromium (usually it contains a

minimum of 10.5% by mass of chromium), and other elements in order to protect the metal against corrosion and other unwanted chemical reactions. The market demand for this metal has doubled over the past decade with an annual production amounting to over 2.5×10^7 t. The recycling of stainless steel is especially important as it saves natural resources including the different alloying metals which are beginning to show signs of future depletion. Today, an ordinary stainless steel product is composed of about 60% recycled material [2].

2.2 Nonferrous Metals

The most commonly used NF metals in the world today are aluminum, copper, brass, zinc, and lead. Because of their limited availability, their high value, and the considerable energy saved if recycled, large quantities of these NF metals are reclaimed and recycled in smelters, refineries, foundries in most countries of the world. This is not only ecologically sound (up to 99% reduction of CO₂ emissions) but also energy efficient (80%–95% savings). The following list of percentages of recycled metals in new products gives some idea of the scale of recycling and its importance: aluminum >33%, copper >40%, zinc >30%, and lead >35% [3].

3 MANAGEMENT OF METAL WASTE

The essential demands of modern waste management are to reduce the total amount of waste arising and to reuse and recycle as much of the waste as possible. In many fields of recycling, it is difficult to meet these requirements because the recovered products are often of reduced quality and hence value. As a result, these materials can only be used in a downgraded form. A typical example is the recycling of waste plastics. In most cases the collected material is of mixed types of plastic which are not easy to

recycle. Mixed plastics can, however, be used in the production of components with inferior properties.

However, for metal recycling the situation is very different. The most important reason for this is that metal can be recycled indefinitely and that subsequent metallurgical treatments do not substantially change the physical and chemical properties of the metal. Furthermore, metals (including recycled metals) have a high market value which is very rare in the recycling industry. Here, with metals, supply and demand are the determining factors that affect the market prices. Moreover, the prices can be influenced to a certain degree by operators of recycling plants as they have the chance to sell their products at convenient points of time, that is, when adequate revenues can be achieved and the “price is right.”

In general, the recycling industry for metals is structured in an organizational form of a pyramid: at the bottom of the pyramid are many small companies which purchase and collect scrap metal. This scrap is then sold to larger business establishments which process and separate the metals and finally it is sold to companies which have metallurgical plants for further treatment.

4 METAL CONTAINING RAW MATERIALS FOR RECYCLING

Scrap metal is made up of a mixture of metals originating from a variety of sources which include commerce and industry, municipalities, and households. This obsolete scrap is collected, stored, processed, and sold from scrap yards or other specialized facilities. In this context “home” scrap and “in-house” industrial scrap are not discussed as these materials can be considered as “works scrap” which never reach the consumer. As a rule this type of scrap does not contain foreign material and does not need any treatment or separation process and can

be reused directly. However, obsolete scrap requires target-oriented mechanical processing in order to meet the quality demands of the customers which at this stage are metallurgists at metallurgical plants. At this stage, the following goals are to be achieved:

- modifications of physical properties, for example, dimensions and bulk densities,
- modifications of chemical properties, for example, metal content and unmixed grades of final products,
- modifications of safety properties, for example, removal of explosives and hollow bodies,
- modifications of other properties, for example, separation of different metals and separation of unwanted adherences.

The collected scrap appears in a great variety of forms and properties such as different lump sizes and shapes; materials with differing bulk densities; different kinds of metals, each with their own properties (e.g., hardness, abrasiveness, etc.); and materials made of composite substances which could include plastics and other nonmetals. Consequently, it is necessary to adapt the treatment processes to the special characteristics of the most frequently found complex composed feed mixtures. Mechanical processing of scrap is carried out predominantly with mechanical equipment, such as shears, compaction units, shredders, and other types of machines. [Table 10.1](#) presents an overview of the different kinds of scrap and the mechanical processing methods used in recovering the different metals.

5 MACHINERY AND PROCESSES FOR SCRAP TREATMENT

In the following section, typical machinery and processes used for scrap treatment are described. The most relevant machines which are employed in practice are listed in [Table 10.2](#).

TABLE 10.1 Examples of Different Scrap Types and the Possible Processing Methods Employed

Type of Scrap (Fe- and NF-Metals)	Potential Processing Method
Light mixed consumer scrap, end-of-life-vehicles (ELVs)	Comminution with shredder, subsequent separation with air classifier, magnetic separator, and handpicking
Waste of electric and electronic equipment (WEEE)	Comminution with hammer mill, subsequent separation with air classifier, magnetic separator, and other equipment
Cable scrap	Comminution with rotor shears and granulators, subsequent separation with air tables, and other equipment
Ash from waste incineration including Fe- and NF-metals	Classifying with screens, comminution with shredder, subsequent separation of metals
Mixed stainless steel scrap	Comminution with hydraulic shear or shredder, subsequent separation of metals
Intermediate metal products from waste sorting plants	Comminution with hammer mill, subsequent separation with magnetic and eddy current separators, and other equipment
Sheet metals and residues of stamping	Compaction with scrap press
Fe- and NF-turnings	Comminution with turnings crusher, subsequent separation of cutting fluids with centrifuge, magnetic separator
Heavy scrap with wall thicknesses up to 150mm	Comminution with hydraulic scrap shear, where necessary with subsequent screening of fines
Heavy scrap with wall thicknesses more than 150mm	Comminution with flame cutting or blasting
Cast iron scrap	Comminution with vertical drop work

5.1 Scrap Shears

Guillotine shears are used in most industrialized countries for the cutting up of lumpy, thick walled steel and NF metal scrap, the majority of which is reasonably ductile. In the process, the material is usually stressed by compressing and shearing forces. The desired goal of this cutting process, using the hydraulic shears, is to achieve a single-stage reduction of the scrap to dimensions with a final length of approximately 400–1000mm. The process meets the demands of steel mills, foundries, and NF metal smelters regarding the physical properties and the condition of the metals. Thus all types of scrap from more compacted steel plates, pipes, and beams as well as bulky scrap in the form of tanks,

casings, and structural elements can be cut into similar sized pieces.

The functioning operation sequence of guillotine shears is characterized by spatial precompression with a side press, a press lid, and a feeding pusher forming a compact cord which is pushed underneath the cutting blade. This allows the scrap to be cut into pieces of variable length [4].

However, it is not possible to obtain a complete separation of complex and compounded material such as metal/metal or metal/nonmetal composites from the pieces cut with these scrap shears. Therefore the application of guillotine shears is limited to the processing of materials containing a minor quantity of foreign substances. Such shears are predominantly operated in steady

TABLE 10.2 A Selection of Machinery and Equipment Employed in Metal Processing

Machines	Typical Applications
<i>For comminution</i>	
Hydraulic guillotine shears	Comminution of heavy, bulky, and long scrap constituents
Alligator shears	Comminution of bulky and long scrap constituents
Rotor shears	Comminution of cable and WEEE scrap
Granulators	Comminution of cable scrap
Rotor impact mills	Comminution of WEEE and shredder residues
Grinder mills	Comminution of light mixed scrap, compaction of cooling scrap
Preshredders	Precrushing of ELVs, subsequent processing with shredder
Shredders	Comminution of light mixed scrap and ELVs
Hammer mills	Comminution of turnings, WEEE, and metal cans
Cross-flow crushers	Comminution of WEEE and metal cans
Single shaft crushers	Comminution of WEEE and metal cans
<i>For screening</i>	
Drum screens	Classification of cooling scrap, turnings, and shredder residues
Vibrating screens	Classification of shredder residues
Flip-flow screens	Classification of shredder residues
<i>For separation</i>	
Magnetic separators	Separation of magnetizable waste items especially Fe metals
Eddy current separators	Separation of electrically conductive waste items like NF metals
Corona roll separators	Separation of metals from nonmetals in the size range <4mm
Air classifiers	Separation of lights, for example, like shredder fluff
Cyclones	Separation of air classifier lights from the carrier air
Air tables	Separation of metals from nonmetals
Sensor-based sorting devices	Separation of nonferrous metals and stainless steel mixtures
Heavy media separators	Separation of NF metals like Mg and Al from shredder heavy fraction
Wet shaking tables	Separation of NF metals <2mm from WEEE processing
<i>For compaction</i>	
Baling presses	Compaction of metal sheets and cans
Briquetting presses	Compaction of turnings

continuous operation. The required electrical power ranges from about 300 to 900 kW and the shearing forces can be as much as 14,000 kN [4].

5.2 Shredders and Shredder Plants

There are about 900 shredder plants installed worldwide [5] and these plants are used mainly for the processing of light mixed scrap metal and ELVs. The first step in these plants is the shredder itself which has the task of crushing and liberating the feed material by intensive impact and shearing stresses. As can be seen in Fig. 10.1 the input material slides via an inclined chute into the shredder. The scrap is then seized and compacted by the feed rollers (1). The feed rollers are automatically controlled in order to avoid current peaks. Consequently, a load-dependent shredder operation can be guaranteed. At the edge of the anvil (2) the in-feed material is grasped by the fast rotating hammers which have a circumferential velocity of up to 70ms^{-1} and the scrap is stressed and disintegrated by the shearing forces. The hammers, which are suspended on the carrying shafts of

the rotor, force the disintegrated scrap pieces into the interior of the shredder where they are further stressed by impact and by flexing.

The baffle plate edge (3) and the baffle plate (4) are structurally formed in such a way that ductile metals are further crushed and compressed until they are small enough to pass through the grid (5). The position of the grid (11) can be adjusted hydraulically. The adjustment determines the final grain size and the compression ratio. As a rule, the steel scrap produced in shredder plants is compressed so that a bulk density of 1 t m^{-3} can be achieved. The discharge of the crushed material from the shredder is carried out via a vibrating conveyor (8) and a conveyor belt. If heavy scrap lumps are found in the shredder and cannot be further crushed, an ejection flap (7), operated manually or automatically, can be opened in order to discharge these bulky pieces. A branch connection (6) to the dedusting system of the shredder plant fulfills the demand of a largely emission-free operation.

The material which is discharged through the shredder grid has a very broad grain size distribution ranging from coarse (approx. 150 mm)

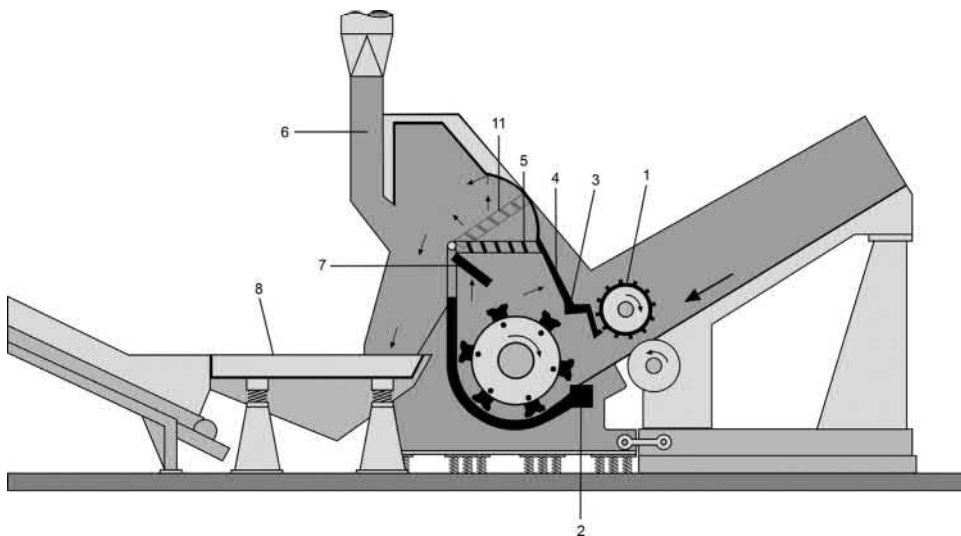


FIG. 10.1 Schematic view of a shredder [6].

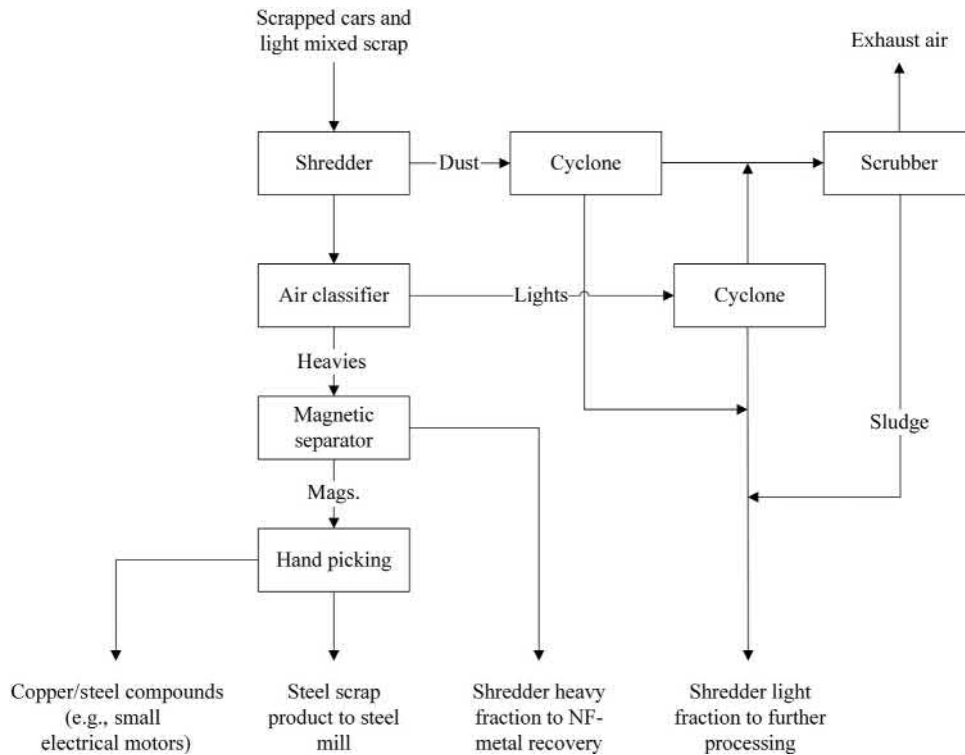


FIG. 10.2 Example of a simplified flow sheet for shredder plants.

to very fine particles (<1 mm). As can be seen in the simplified flow sheet of Fig. 10.2, the crushed material is then fed into an air classifier. This device separates light constituents from the remaining heavy particles (heavies) in a rising air current. The proper adjustment of the air classifier velocity is the determining factor in the amount of misplaced heavy material, especially metals in the light fraction. There is always a compromise necessary as the heavy material needs to be free, to a certain extent, of bothersome fluffy materials. Fines which cannot be separated by the cyclones are segregated very effectively from the carrier air together with a subsequently arranged scrubber. The separated shredder light fraction amounts to approximately 18%–25% by weight of the shredder input [7].

Within the heavy fraction of the air classifier, the metals are enriched. In most cases magnetic

drum separators are employed for the selective separation of the iron and steel scrap—this accounts for approx. 65%–75% by weight of the shredder in-feed material. After handpicking for the removal of nonliberated copper containing items, for example, parts of electric motors, the final ferrous product fulfills the quality demands concerning the grade and the bulk density in order to be recycled in steel mills without further treatment. The material which is not attracted by the magnetic separator—the so-called shredder heavy fraction—is an intermediate product (3%–8% by weight of shredder input) containing NF metals. The processing of this fraction allows recovering valuable metals such as aluminum, copper, zinc, bronze, lead, magnesium, and stainless steel. In total approximately 50%–60% by weight of metals are to be found in the heavy fraction [7].

5.3 Processing of the Shredder Heavy Fraction

Further processing of the shredder heavy fraction, with the main aim to recover NF metals, mainly occurs in specialized plants which, however, very rarely belong to the downstream equipment of shredder plants. A

simplified flow sheet of such a plant illustrating the state of the art for the processing of NF-metal-rich mixtures is shown in Fig. 10.3. In the first step, a screen divides the feed material into four fractions with the intention of reducing the width of the grain size distribution in the screen products thus improving their sorting capabilities. The ranges of the generated grain

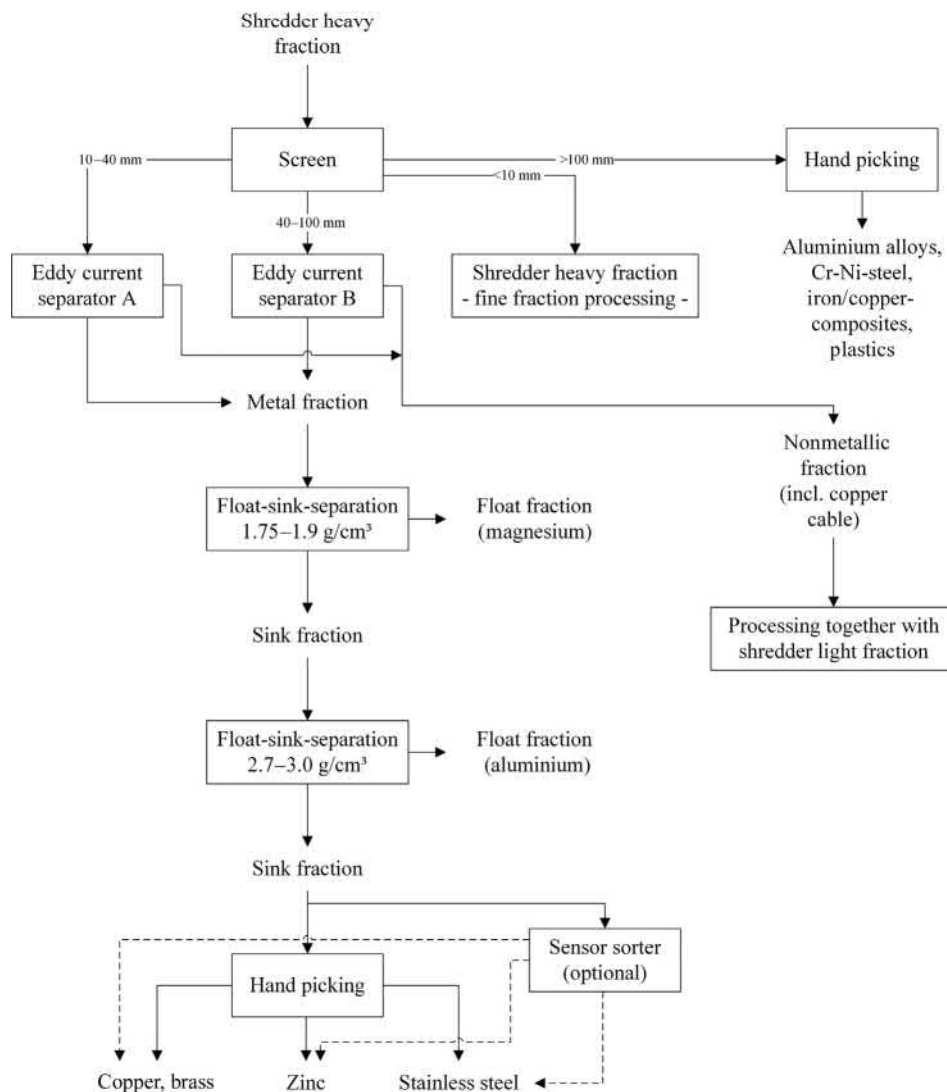


FIG. 10.3 Example of a simplified process for the treatment of the shredder heavy fraction [7].

size are important and can be modified. The screen overflow is directed to a handpicking station where NF metals and stainless steel are separated.

The screen underflow fractions (10–40 mm; 40–100 mm) are then further processed on eddy current separators. These devices are very effective in segregating a good portion of the NF metals contained in the mixture [8].

The segregation efficiency of eddy current separators depends to a great extent on the physical properties of the feed material. These are mainly the grain size range, the grain shape, and the ratio of the electrical conductivity to the density of the metallic components. With these systems, some metals such as wires, metal/non-metal compounds, lead, as well as stainless steel cannot be deflected and remain in the so-called tailings fraction for further processing.

Two heavy media separators are applied for the density separation of the NF metal mixture from the preceding process stages. A separation into three products (magnesium, aluminum, and a mixture of heavy metals) can be conducted based on the different densities using heavy liquids of densities of between 1.75 and 3.0 g cm⁻³. Following this is an additional handpicking station which, as far as is possible, provides a separation of NF metals and stainless steel. Sensor-based sorters are optional to the handpicking and can be employed in order to separate the NF metal remainders. The recovered metals from such plants are final products which can be sent directly to metallurgical plants without further treatment.

For the removal of stainless steel items, sensor-based sorters with inductive metal detectors are applied (q.v. Section 5.5).

The fraction <10 mm is passed on to specialized plants for further fine grain processing.

Currently, most of the nonmetallic residues are processed together with the shredder light fraction in order to either recover plastics and rubber or to be used as refuse derived fuel (RDF).

5.4 Processing of NF Metals From Incinerated Bottom Ash

In a waste incineration plant, different by-products are produced. Volume and mass of the processed waste are reduced by the incineration process. The largest amount of residual material is bottom ash and up to 15–30 mass% or 10–20 vol.% remain as bottom ash. There are two different techniques in order to discharge the bottom ash after combustion: wet or dry. A wet discharger is commonly used and the bottom ash ends up with a water content of about 15–25 wt% [9].

The varying composition of the incineration input material and the applied technology leads to various physical and chemical properties of the bottom ash. Additionally, the bottom ash is subject to regional and seasonal fluctuations [10]. Nevertheless, bottom ash can be characterized by three superordinate fractions: metals, unburnt material, and minerals (Table 10.3).

Ferrous metals have the highest proportion of the metals fraction of around 8 wt%, while NF metals have a proportion of about 2 wt%. In addition to ferrous and NF metals, stainless steel (1 wt%) can also be found in the bottom ash [12]. The fraction of metals consists predominantly of cans, caps, aluminum in various alloys, brass, copper, and other metallic products (e.g., faucets, tool wrenches) [13].

The term “unburned” covers materials which have been incompletely burned. These residues mainly consist of paper, wood, plastic, or textiles [10]. The mineral fraction mainly consists of concrete, bricks, stones, slag chunks, glass, ceramics, and porcelain [14]. Depending on the incineration temperature, materials sinter and

TABLE 10.3 Composition of Bottom Ash [11, 12]

Fraction	Quantity
Metals	7–12 wt%
Unburnt material	1–5 wt%
Minerals	84–90 wt%

form agglomerates, consisting of, for example, molten metal or glass and ash [8, 12].

A bottom ash processing plant, according to the current state of the art, consists of robust units, which ensure almost interference-free operation [12]. Such bottom ash processing plants combine the following components [10] (Fig. 10.4):

- multilevel sieving,
- magnetic separation (separation of ferrous metals),
- eddy current separation (separation of NF metals),
- induction sorting system (separation of VA steel) (optional),
- handpicking (cleaning of ferrous fraction, separation of copper coils).

A guard grate to separate coarse material >400 mm is the first processing step. The material <400 mm is divided into several grain size fractions so that the material can be processed

by the following (treatment/sorting) units. Magnetic and eddy current separators operate optimally when the grain size (length and width) has a ratio of about 3 to 1. In some plants, the eddy current separation in the grain class 10–80 mm is followed by an inductive sorting system to identify and separate VA steel [15, 16].

In the last decade, the main focus of the bottom ash treatment switched from conditioning of minerals to the separation of metals. This shift in processing targets was accompanied by the fact that the largest mass fraction of bottom ash, the fine material <10 mm, has been the focus of technical development. Thus the treatment processes moved with an adapted sieving and NF metal sorting technology even further toward fine grain sizes. In conjunction with a conventional storage and aging of the bottom ash before processing, the application limit for conventional dry mechanical treatment moved to a grain size of about 2 mm.

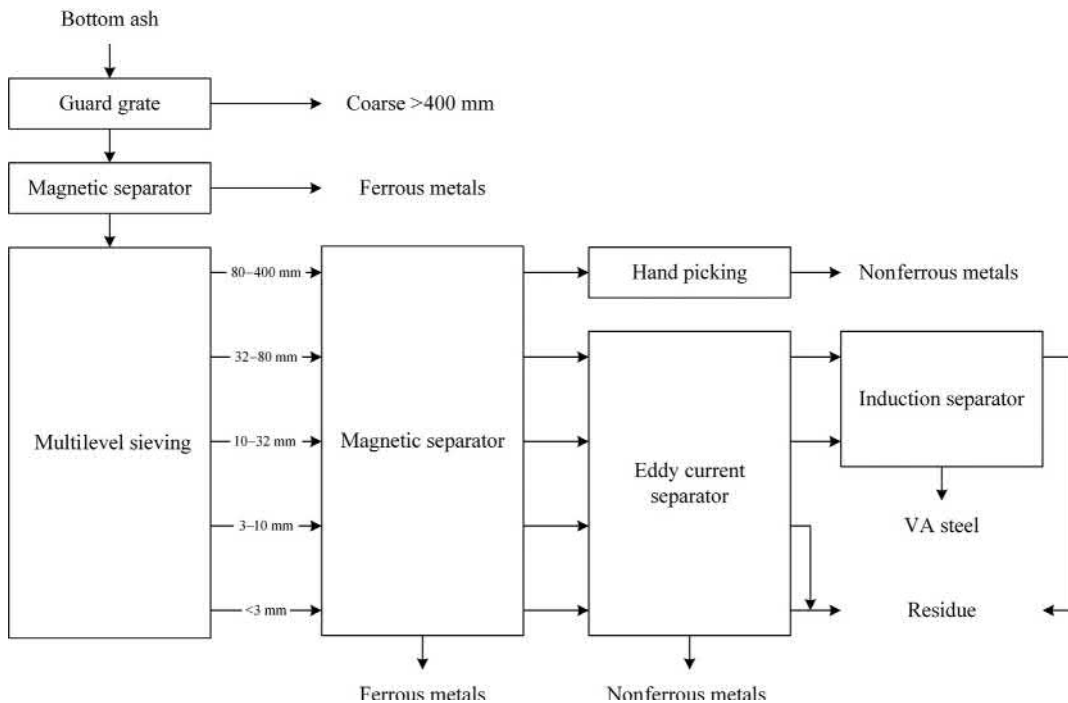


FIG. 10.4 Flowchart of a state-of-the-art bottom ash treatment plant.

5.5 Sensor-Based Sorting for Metal Recycling

Single grain separation using externally identifiable properties, which can be determined with suitable detectors, is defined as sensor-based sorting. This technology has revolutionized the design of dry working processes in the field of waste treatment over the past 30 years [17]. In principle, most of modern sensor-based sorting machines consist of a conveyance system for dissemination and singling of the feed material, a sensor system for the recognition of specific material properties, a software-controlled electronic device for the interpretation of data received from the sensor system, and a discharge device for the separation detected components. Today, newly developed machines are often equipped with a combination of different sensors in order to recognize multiple material properties in a single step whereas the sensor data are evaluated in real time by a computer system. Consequently, these machines guarantee a better separation efficiency in comparison with single sensor devices, especially for sorting of complex material mixtures with a large range of qualitative characteristics. A distinct advantage of modern machines is their learning aptitude, which is based on software-controlled data processing. This feature allows

an increased adaptability especially with regard to changes of the process flow sheet, the input material composition, or altered demands concerning the product quality of the recovered materials.

In order to achieve effective separation with sensor-based sorters, it is very important to condition the feed material before entering the detection zone so that the different components of the feed material can be recognized by the sensors. Thus single particles should not touch or overlap each other. The most common method of achieving this is to employ a cascade of different belt conveyors and/or inclined sliding chutes with increasing transport velocities. The application of sensor-based sorters, in recycling processes, has great advantages in comparison with conventional methods. This is becoming increasingly more beneficial as new separating criteria for separation are made accessible. In addition, the continuous development of new sensor systems continues to opening up innovative fields related to separation and recycling and remarkable progress concerning novel sensors and sensor combinations has been achieved over the past few years.

A number of different types of sensor sorters have entered the market in the last decade especially designed for the separation of metals. Table 10.4 gives an overview of the different

TABLE 10.4 Sensor-Based Sorters for Metal Separation and Typical Applications

Separating Attribute	Sensor Technology	Examples for Separation of
Color, brightness	Line scan color camera	Copper and brass from NF metal mixtures, printed circuit boards from WEEE
Electrical conductivity	Inductive detector	Metals from diverse waste mixtures, stainless steel from waste mixtures
Density	X-ray transmission sensor	Aluminum and magnesium from metal mixtures, WEEE from waste mixtures
Spectral analysis	X-ray fluorescence sensor	Copper meatballs from ferrous shredding fraction
Chemical composition	Laser-induced breakdown spectroscopy	Different aluminum and steel alloys from metal mixtures

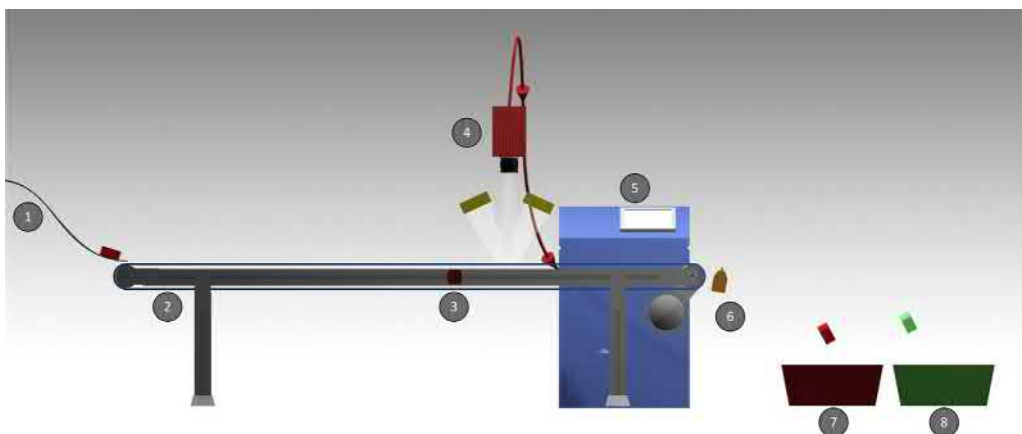


FIG. 10.5 Principle of inductive sensor sorter with additional line scan camera.

types of sorters, the employed separating attributes, as well as typical applications.

Today, sensor-based sorters with inductive detectors are frequently used for metal separation. The assembly and functioning principle of such devices are to be seen in Fig. 10.5 [18]. This type of automatic picking is a combined opto-electronic system which can operate with a belt width of 600 mm or 1200 mm. It combines the special characteristics of an optical system incorporating a high-speed camera with recognition of 16.7 million colors and a special conductivity sensor permitting the identification of practically all metals. The machine can handle mass streams of up to 10 tonnes per hour, for instance, in the size class 15–50 mm. With a belt width of 1200 mm, 160 air nozzles are employed to blow out the detected materials.

A vibrating feeder (1) and a belt conveyor (2) running with a speed of 3 ms^{-1} are used to line up the particles on the belt into a single layer. The metal sensor (3) which is located under the conveyor belt delivers the initial characteristics of each single metal particle to the computer. In addition, the camera (4) analyses the size, shape, color, and position of particles on the belt. The information from both sensors is then transferred to an electronic system (5) which

evaluates the data and generates the impulses and instructing the nozzles (6) to blow out single particles or allow them to pass. The declined (7) and the accepted (8) products are transported by individual belt conveyors for further treatment or for storage.

A similar setup is used for XRF by replacing the line scan camera by an XRF sensor and the illumination by an X-ray source where the spectral information of an object regarding its composition is used for classification. The main use case is the separation of rotors of alternators from the iron fraction of shredded automobiles in which the heavily copper-coiled rotors are undesired due to their high copper content. The rotors are initially magnetically separated into the ferrous fraction due to their iron core.

The XRT technology is usually used for the automated separation of heavy and light NF metals based on their proton number. In this scenario X-rays from a source travel through the material and are registered by a sensor on the opposite side. The registered attenuation of the X-rays correlates with the proton number and the thickness of the material. In order to compensate for the influence of the thickness, two different wavelengths/energies of radiation are used. This technique is termed Dual-Energy-XRT (DE-XRT).

6 CONCLUSION

Mechanical treatment of different waste streams containing metals involves the use of well-established methods, which as a rule, is profitable because of the high market value of the recovered metals and also because metals do not change their properties with use and hence can be recycled an unlimited number of times. The main aim of the processing methods is to achieve high recovery values as well as the best possible grades of the final metallic products. Sensor-based sorters are implemented additionally to improve separation efficiencies. Finally, resmelting of the reclaimed products constitutes the closing of the complete recycling loop for metals.

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Radioactive Waste Management

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1 INTRODUCTION

The ore pitchblende was discovered in the 1750s near Joachimstal in what is now the Czech Republic. Used as a colorant in glazes, uranium was identified in 1789 as the active ingredient by chemist Martin Klaproth. In 1896 French physicist Henri Becquerel studied uranium minerals as part of his investigations into the phenomenon of fluorescence. He discovered a strange energy emanating from the material which he dubbed “rayons uranique.” Unable to explain the origins of this energy, he set the problem aside.

About 2 years later, a young Polish graduate student was looking for a project for her dissertation. Marie Sklodowska Curie, working with

her husband Pierre, picked up on Becquerel’s work and, in the course of seeking out more information on uranium, discovered two new elements (polonium and radium) which exhibited the same phenomenon, but were even more powerful. The Curies recognized the energy, which they now called “radioactivity,” as something very new, requiring a new interpretation, a new science. This discovery led to what some view as the “golden age of nuclear science” (1895–1945) when countries throughout Europe devoted large resources to understand the properties and potential of this material.

By World War II, the potential to harness this energy for a destructive device had been recognized and by 1939, Otto Hahn and Fritz Strassmann showed that fission not only released a lot

of energy but that it also released additional neutrons which could cause fission in other uranium nuclei leading to a self-sustaining chain reaction and an enormous release of energy. This suggestion was soon confirmed experimentally by other scientists and the race to develop an atomic bomb was on. The rest of the development history which lead to the bombing of Hiroshima and Nagasaki in 1945 is well chronicled. After World War II, development of more powerful weapons systems by the United States and the Soviet Union continued to advance nuclear science. It was this defense application that formed the basis for the commercial nuclear power industry.

1.1 The Dawn of the Commercial Nuclear Power Industry

Both the Soviet Union and the West realized that the tremendous heat produced in the process could be tapped either for direct use or for generating electricity. It was also clear that this new form of energy would allow development of compact long-lasting power sources which could have various applications. The first nuclear reactor to produce electricity was the Experimental Breeder Reactor (EBR-1) in Idaho, United States December 1951. In 1953 President Eisenhower proposed the “Atoms for Peace” program, which reoriented significant research effort toward electricity generation and set the course for civil nuclear energy development in the United States. The main US effort was under Admiral Hyman Rickover, which developed the Pressurized Water Reactor (PWR) for naval (particularly submarine) use. The PWR used enriched uranium oxide fuel and was moderated and cooled by ordinary (light) water. The Mark 1 prototype naval reactor started up in March 1953 in Idaho and led to the US Atomic Energy Commission building the 60MWe Shippingport demonstration reactor in Pennsylvania, which started up in 1957 and operated until 1982. The Shippingport reactor spurred the commercial nuclear power industry in the United States.

Similar development occurred across the globe and today there are almost 450 reactors of varying configurations operating throughout the world with a total installed capacity of over 390GWe or about 11% of the world’s electricity (vs. coal—40%, oil/natural gas—22%, hydro—17%, solar/wind—3%, and other—7%) [1]. Today, some view that the nuclear industry is at the eye of a “perfect storm.” Fuel oil and natural gas prices are escalating while worldwide energy demands are increasing at an alarming rate. This coupled with increased concerns about greenhouse gas (GHG) emissions has caused many to look negatively at long-term use of fossil fuels. This convergence of factors has led to a growing interest in the revitalization of the nuclear power industry across the globe. The World Nuclear Association projects a 30% increase to 510GWe in operation in 2030 and overall 41% increase to 552GWe in 2035. The World Nuclear Association has put forward a more ambitious and effective scenario than this, proposing the addition of 1000GWe of new nuclear capacity by 2050 to provide 25% of electricity then (10,000 TWh) from 1250GWe of capacity (after allowing for 150GWe retirements by then). This would require adding 25 GWe per year from 2021, escalating to 33 GWe per year, which is not much different from the 31 GWe added in 1984, or the 1980s overall record of 201 GWe total. Taking nuclear power output to a quarter of the world total electricity production would have a very positive effect on air quality, reducing CO₂ emissions, and boosting energy security without the complications of working around dispersed and intermittent renewable sources.

1.2 Radioactive Waste Generation

As with any industrial process, commercial nuclear power results in the generation of process wastes. To facilitate communication and information exchange regarding treatment and handling of radioactive wastes, the IAEA instituted a revised waste classification system in

1994 that takes into account both qualitative and quantitative criteria [2]. As defined later, the IAEA developed a system to classify these wastes in three principal classes including Exempt Waste, Low- and Intermediate-Level Waste (LILW), and High-Level Waste (HLW). (Note: The quantitative cutoff points for each class of waste vary from country to country, typically associated with radiation risk to the public, which depends on storage and/or disposal characteristics. The IAEA has provided general guidelines and these are noted as follows.)

Exempt Waste: (EW) contains such a low concentration of radionuclides that it can be excluded from nuclear regulatory control because radiological hazards are considered negligible. Per the IAEA, the definition of EW is based on an annual dose to members of the public of less than 0.01 mSv.

Low and Intermediate Level Waste: (LILW) contains enough radioactive material that it requires actions to ensure the protection of workers and the public for short or extended periods of time. This class includes a range of materials from just above exempt levels to those with sufficiently high levels of radioactivity to require use of shielding containers and in some cases periods for cooling off. LILW may be subdivided into categories according to the half-lives of the radionuclides it contains, with “short-lived” being less than 30 years and “long-lived” greater than 30 years. The IAEA suggests limiting concentrations of short-lived isotopes to less than 4000 Bq g^{-1} in an individual waste package and concentrations of long-lived isotopes to less than 400 Bq g^{-1} in a waste package.

High Level Waste: (HLW) contains sufficiently high levels of radioactive materials that a high degree of isolation from the biosphere, normally in a geologic repository, is required for long periods of time. Such wastes normally require both special shielding and cooling periods. In the IAEA guidelines, HLW contains thermal power above 2 kW m^{-3} and concentrations exceeding those for LILW.

Substantial amounts of radioactive waste are generated through civilian applications of radionuclides in medicine, research, and industry. A typical 1000 MWe nuclear power station produces approximately 300 m^3 of LILW per year and some 27 t (27 tonnes) of high-level solid packed waste per year. By comparison a 1000 MWe coal plant produces some 270,000 t of ash alone per year containing radioactive material and heavy metals which end up in landfill sites and in the atmosphere [3]. Worldwide, nuclear power generation facilities produce about $200,000 \text{ m}^3$ of LILW and $10,000 \text{ m}^3$ of HLW (including used fuel designated as waste) each year.

In the development of new nuclear reactors, waste management restrictions are part of the analytical package assessing the sustainability of the design. An organization called Generation IV International Forum (GIF) has been created with the mandate to examine the six new types of reactors under development. These include:

- Gas Cooled Fast Reactor (GFR)
- Sodium Cooled Fast Reactor (SFR)
- Supercritical Water Cooled Reactor (SWCR)
- Very High Temperature Reactor (VHTR)
- Molten Salt Reactor (MSR)
- Lead Cooled Fast Reactor (LFR)

Each technology has its own advantages over the reactors now in operation, but one of the main objectives is to minimize and manage nuclear waste so as to reduce the long-term stewardship burden.

Another technology, termed Small Modular Reactors (SMR), is also under development. They are termed “modular” because they can be constructed in small parts. With a generally smaller physical footprint and faster construction timetable, the advantages over the current reactor design are obvious.

However, waste management issues still must be addressed. Because the reactors may be placed underground, there is some concern that removal of the used fuel can be problematic.

The removal of used fuel and general maintenance of the reactor is expected to be facilitated by the specific modular design. Also, because there will be more of them compared to current reactors, there may be an actual increase in the amount of used fuel generated. It is not yet clear whether or not there will be an increase in waste produced per unit of energy produced. Some of the SMR designs are sodium or potassium cooled which present a further complication in waste management. The type of waste generated is no different from the current design [4].

2 NUCLEAR WASTE TREATMENT AND PROCESSING

Research studies into the management of radioactive waste began in the 1930s. As the commercial nuclear industry evolved through the 1960s and 1970s, additional emphasis was placed on developing long-term solutions for radioactive wastes. Exempt and LILW from commercial nuclear power facilities are handled much like ordinary municipal wastes, although most LILW is disposed of in stable near-surface disposal sites, or as is the case with transuranic waste (TRU) from the US defense program in stable salt-based repositories (such as the Waste Isolation Pilot Plant, WIPP in New Mexico, United States).

In 2007, in response to growing concerns about management of LILW in the United States, the US Government Accountability Office (GAO) performed a comprehensive review of worldwide practices associated with LILW handling [5]. This report provides a comprehensive analysis of management approaches for LILW, including soil, debris, rubble, process materials, and clothing that have been exposed to radioactivity or contaminated with radioactive material. The report also looked at disposition of excess sealed radiological sources that are no longer useful for industrial or medical applications. The GAO found that most countries maintain waste inventory databases that include information on waste

generators (nuclear utilities, hospitals, universities, and research laboratories), waste types, storage locations, and present and future waste generation predictions and disposal capacity needs. The report also found that disposal practices vary according to the hazard presented by the LILW in question. As discussed before, lower activity LILW is handled much like municipal waste and is typically disposed in near-surface burial sites that are monitored over time. Depending on the level of activity being treated, most of this disposal is handled as Exempt Waste per the IAEA definitions (see earlier) and no review is required from the nuclear regulatory authority. For higher activity LILW, most countries have centralized storage and disposal options that are licensed by the appropriate nuclear regulatory authority. Funding for operations of these facilities is either provided by the central government or by collecting disposal fees at the time of disposal. For sealed sources used in industrial and medical applications, the disposal fee is often collected at the time of purchase.

The discussion in the remainder of this chapter will focus on handling of used nuclear fuel and HLW. A typical 1000MWe nuclear reactor generates about 23t of used fuel each year. In the United States and Canada, this used fuel is regarded as waste and is slated for direct disposal. In most of Europe and Japan, the used fuel is reprocessed to recover unused uranium and to efficiently manage TRU and fission products. France is widely considered to be the world leader in commercial nuclear fuel recycling, although Russia also has several decades' worth of reprocessing experience. The French program utilizes state-of-the-art processing facilities at La Hague in northern France and utilizes both the recovered uranium and plutonium to produce mixed oxide fuel (MOX, see discussion later). The Japanese have worked extensively with the French and are currently commissioning a reprocessing facility in Rokkasho. Countries such as India and China have emerging reprocessing programs associated with the increase in nuclear power generation in those countries.

In either reprocessing or direct disposal, the used fuel is first stored for several years under water in cooling basins at the reactor site (see Fig. 11.1). The water covering the fuel assemblies provides radiation protection, while removing the heat generated during radioactive decay.

If the used fuel is reprocessed, the nuclear fuel assemblies are disassembled and chopped into small pieces in a highly secure, remote processing environment. The fuel core is typically dissolved in nitric acid and separated chemically into uranium, plutonium, and high-level waste solutions. About 97% of the used fuel can be recycled leaving only 3% as high-level waste. The resulting hulls from the fuel assemblies are treated as LILW.

For a typical 1000MWe nuclear reactor, about 230 kg of plutonium (1% of the used fuel) is separated in reprocessing annually. The separated

Pu can be used in fresh MOX fuel or stored for later handling and disposal. MOX fuel fabrication has been ongoing in Europe, with some 25 years of operating experience. A similar plant is operating in Japan and all Japanese reactors are capable of operating on MOX fuel. A MOX fuel plant is also under construction in the United States (at the Savannah River Site in Aiken, South Carolina) for disposition of excess Pu from the US nuclear weapons program.

Due to the presence of long-lived radionuclides, the separated high-level wastes (about 3% of the typical reactor's used fuel) needs to be isolated from the environment. Research into the processing and disposal of HLW has been active for many years. Isolation of the HLW has typically been in large underground storage tanks. In the United States, about 284 ML (284 m³ or 75 million gallons) have been stored in 177



FIG. 11.1 Typical cooling basin for used nuclear fuel. From the Nuclear Energy Institute © 2016. NEI. All Rights Reserved.

tanks at Hanford, 53 tanks at Savannah River, and two tanks at the West Valley Demonstration Project. The HLW is in the form of a liquid or slurry and needs to be solidified into a waste form before transport to a final storage/disposal facility.

Development of appropriate waste forms began in the United States in the late 1940s at the Brookhaven National Laboratory [6]. The materials studied were based on montmorillonite clay and phosphate glass. France began making borosilicate glass in 1963 [7]. Over the years, a wide variety of materials have been developed and studied for the ultimate isolation and disposal of HLW. The list includes:

- borosilicate glass
- SYNROC
- porous glass matrix
- tailored ceramic
- pyrolytic carbon and SiC-coated particles
- FUETAP (and other) concretes
- glass marbles in a lead matrix
- plasma spray coatings
- phosphate glass
- titanate ceramic
- various calcines

In the late 1970s, the United States Department of Energy (DOE) formed an alternative waste form peer review panel consisting of prominent, independent engineers and scientists with expertise in materials science, ceramics, glass, metallurgy, and geology [8]. Using a rating process to evaluate the relative merit of all the various proposed waste forms, the panel selected borosilicate glass as the reference waste form.

Borosilicate glass is now the material of choice for incorporating and immobilizing the potentially hazardous radionuclides in HLW. Factors that contribute to the suitability of glass waste forms fall into two main categories. First, glass waste forms possess good product durability. Various glass systems are able to incorporate a variety of waste compositions into durable

waste forms. These forms have demonstrated good chemical and mechanical performance as well as good radiation and thermal stability. Second, waste-glass forms possess good processing characteristics. The technology for making waste-glass forms is both well developed and well demonstrated. Waste-glass forms ranging in size from bench- and laboratory-scale products to multiton canisters have been successfully produced by using ceramic melters as well as in-can melting techniques. The vitrification process provides a substantial volume reduction; a piece the size of a hockey puck (25 mm thick, 76 mm in diameter) would contain the total HLW arising from nuclear electricity generation for one person throughout a normal lifetime [9]. Vitrification has been used for nuclear waste immobilization for more than 40 years across Europe, Japan, and the United States.

In a typical processing facility, the HLW solution is combined with borosilicate glass forming materials and sent to a Joule-heated ceramic melter. Operating at about 1200°C, the smelter turns the waste slurry into molten glass which exits the melter into large stainless steel canisters. An international reference stainless steel canister holds approximately 2000 kg of waste glass. After filling, the canisters are decontaminated and sealed by welding a steel plug into the neck of the canister. In most cases, the canisters are temporarily stored at the vitrification facility prior to eventual transport to a geological repository.

Cement and cement-based materials are used to contain by-products from reprocessing operations that are categorized as LILW. Common advantages of cement stabilization include continuous or batch processing at ambient temperatures, low-cost raw materials, suitability for large or small volumes of many different waste types, and ability to use modular equipment.

Waste stabilization/solidification is most commonly accomplished by mixing aqueous-based wastes with hydraulic or pozzolanic materials such as Portland cements, calcium aluminate cements, calcium sulfo-aluminate (CSA)

cements, magnesium (aluminum) phosphate cements, kiln dusts, fly ashes, and reactive slags. These materials react with water to form insoluble binders. Composite cement systems using several of these phases are commonly used by the nuclear industry. The hydrated binder phases encapsulate solid particles in the waste, coprecipitate selected contaminant species, and adsorb excess water and soluble contaminants. In addition, the aqueous chemistry of the cement-waste mixture can be adjusted so that the soluble contaminants are precipitated from solution simultaneously with the formation of the matrix phases. Mixtures of the cementitious ingredients plus other additives such as sodium silicate (hardening agent), set accelerators, and retarders are commonly used. As a result, a monolithic waste form can be produced at ambient temperatures. The waste forms can also be designed to have a wide range of properties. Compressive strengths typically range from 300 to 20×10^3 kPa (50–3000 psi). Viscosity and set time can also be adjusted to meet mixing and placement requirements dictated by the production process. Composite cements are typically associated with a highly alkali environment that is not suitable for all wastes; Al metal, for example, will corrode in such an environment. As a result, a toolbox of cement systems is being developed including geopolymers, CSA cements, and alkali-activated systems with at least one suitable for all waste types [10].

Hydrated waste forms are typically used for stabilizing aqueous wastes, such as condensed off gas wastes, electroplating sludges, salt solutions, incinerator ash, electrostatic precipitator and bag house wastes, and process residues, such as metal chloride and hydroxide bottoms from ore refining processes. Cementitious materials are also used in a variety of environmental remediation actions to stabilize seepage basin sludges, contaminated soils, and waste disposal sites. In addition, cement-based materials are also used for underground waste tank and

pipeline closures. The standard requirement for this application is subsidence prevention. Portland cement-based grouts or pumpable, self-leveling, self-compacting backfills containing Portland cement are typically used for tank stabilization. Special grout or backfill formulations are also being designed to stabilize residual contaminants which may not have been removed from these tanks.

3 GEOLOGIC DISPOSAL

As discussed before, the HLW fraction of the radioactive waste will require geological isolation for extended periods of time (up to 1,000,000 years). When dealing with such extended time periods, the fate of the stabilized waste is often questioned. In fact, there is a natural example that suggests that final disposal of HLW underground is safe. Over 2 billion years ago at Oklo in Gabon, West Africa, chain reactions started spontaneously in concentrated deposits of uranium ore. Scientists estimate that these natural nuclear reactors continued operating for hundreds of thousands of years, forming plutonium and the other by-products created today in a nuclear power reactor. This same area remained highly saturated following the end of the nuclear reaction. Evidence shows that the materials that would be classified as HLW using the current IAEA guidelines remained where they were formed and eventually decayed into nonradioactive elements; they were not mobile in the environment. It is this natural analog that provides the basis for geological isolation of HLW and/or used nuclear fuel.

Worldwide, countries are working to develop deep geologic disposal facilities for a variety of more radioactive LILW and all forms of HLW. While there is certainly international cooperation in developing programs for geologic disposal, each country has taken a slightly different approach due to differences in geological formation and their domestic nuclear policies. These

repository programs have been ongoing for several decades and as of this writing no country has fully licensed and opened a geologic repository of long-term disposition of radioactive wastes. Sweden will likely have the first licensed repository open sometime after 2015.

Initial discussions regarding a permanent solution to the disposal of high-level radioactive waste in the United States culminated in a report by the National Academy of Sciences—National Research Council in 1957 [6]. The primary recommendation was that “disposal in salt is the most promising method for the near future.” Other report recommendations included stabilization of the waste in a “slag or ceramic material forming a relatively insoluble product,” the potential of disposing of the waste in a deep repository, the separation of Cs^{137} and Sr^{90} , and consideration of the transportation costs.

A generation later, a similar report [11] expanded on the original as a result of the research completed in the interim. This report concluded that the technology for geologic disposal “is predicted to be more than adequate for isolating radioactive wastes.” Other recommendations examined the criterion for system performance, repository design and construction, waste package design, prediction of the performance of the system, and expanded the list of potential host-rock candidates to basalt, granite, salt, and tuff.

Following this report, the United States enacted a policy to dispose of used nuclear fuel and HLW from defense applications at Yucca Mountain, Nevada. The United States maintained this policy for over 20 years and submitted a License Application for the Yucca Mountain Repository to the US Nuclear Regulatory Commission (NRC) in 2008. The Obama administration, however, issued a Presidential decision in 2008 to cancel the Yucca Mountain project and reevaluate disposal alternatives in the United States. The Obama Administration commissioned a “Blue Ribbon Commission” to evaluate alternatives to Yucca Mountain. The

Commission issued its report to the Secretary of Energy in January 2012 [12] and recommended a strategy that has eight key elements:

1. A new, consent-based approach to siting future nuclear waste management facilities,
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed,
3. Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management,
4. Prompt efforts to develop one or more geologic disposal facilities,
5. Prompt efforts to develop one or more consolidated storage facilities,
6. Prompt efforts to prepare for the eventual large-scale transport of used nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available,
7. Support for continued US innovation in nuclear energy technology and for workforce development,
8. Active US leadership in international efforts to address safety, waste management, nonproliferation, and security concerns.

In 2017 the Trump Administration has indicated that it is considering reversing the Obama Administration decision on cancellation of the Yucca Mountain project. This indecision and wavering of policy has been addressed in a recent paper [13] that compared the repository programs of the United States and Sweden. In addition to examining the technological aspects of geologic disposal, this report discusses the regulatory and bureaucratic aspects of the two programs and how those issues affect the success or failure of overall nuclear waste management systems.

The experience in the United States proves that an essential aspect of the waste isolation strategy is that long-term safety of geologic disposal must be convincingly presented, and

accepted, long before a repository can be opened [14]. As discussed before, this requires safety assessments that consider timescales far beyond the normal horizon of societal thinking. For example, it must be acknowledged that the most robust and passively safe system that can be devised by current generations may ultimately be compromised by the actions of a future society, through inadvertent intrusion [14]. These probabilities must be taken into account in assessing the performance of the repository throughout its operational lifetime. Finally, the scientific analysis and decision-making process must involve stakeholders (i.e., regulators, political leaders, public interest groups, and other nongovernment entities) at local-, regional-, and national-levels. A documentary film, *Containment*, has been produced by Peter Galison which discusses many of the aspects of long-term waste management and disposal [15].

4 CONCLUSIONS

Expansion of nuclear energy worldwide is necessary to meet increased power demands and GHG reduction targets. Virtually any international energy forecast predicts large growth in nuclear power generation over the next 30–50 years. The expansion of commercial nuclear power production will result in increased radioactive waste generation. Managing this waste effectively is a critical component of a worldwide “nuclear renaissance” and will continue to be a primary consideration for future nuclear fuel cycles. Past practice has proven the wastes generated from nuclear power generation can be effectively managed using technologies that are well demonstrated at industrial scales, with decades of safe operating practices. As the worldwide community continues to investigate advanced nuclear fuel cycles, radioactive waste management considerations are being given increased emphasis and are, in fact, being considered at the advent of

proposed fuel cycles. This emphasis is necessary to ensure that future nuclear fuel cycles remain economically and *environmentally* competitive (as compared to other forms of energy production) and do not produce legacy waste management issues for future generations.

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The Municipal Landfill

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1 INTRODUCTION

Solid waste comes in many forms, but is usually differentiated as either hazardous or nonhazardous wastes. This differentiation may not be exclusively based on health outcomes, such as toxicity and risk data, but as mentioned in [Chapter 9](#), is also sometimes based on policy or regulatory definitions. For example, large volume wastes that are predicted to present low risks have been exempted from certain rules,

such as sludge from air pollution scrubbers [\[1\]](#) and air releases from farms [\[2\]](#). In the United States, the major statute dictating actions to address solid waste is the Resource Conservation and Recovery Act (RCRA) [\[3\]](#). Municipal solid waste (MSW) also has received such exemptions. For example, sanitary wastes that pass through a publicly or privately owned sewer system are considered domestic sewage and are excluded from regulation under the hazardous waste rules under RCRA [\[4\]](#).

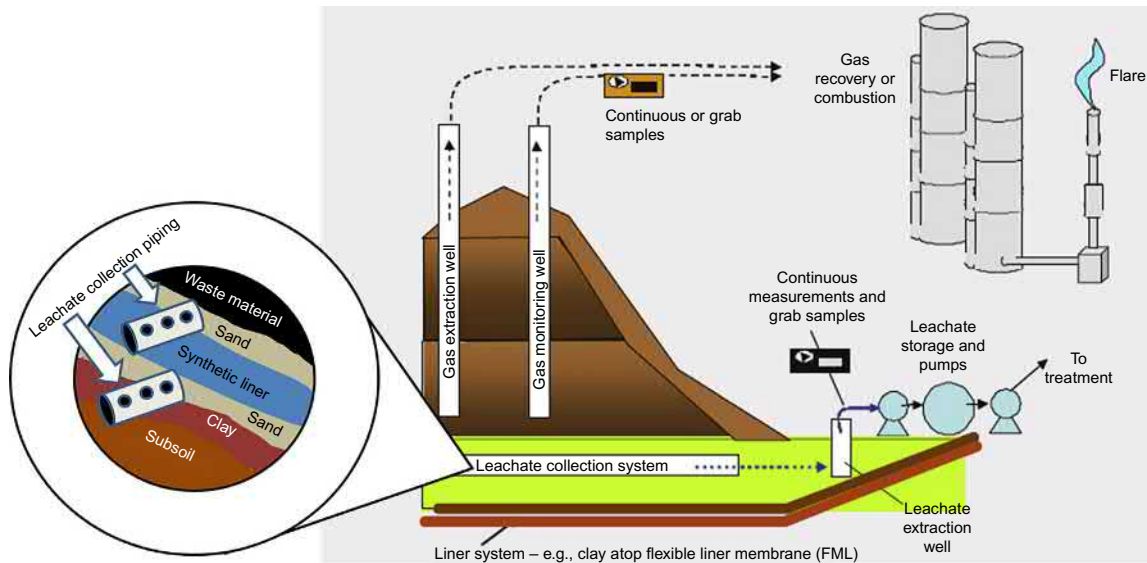


FIG. 12.1 Landfill with leachate collection and gas recovery systems. Although depicted as a linear wall, the leachate collection system surrounds the landfill and consists of layers of sand, geomembrane, clay, and subsoil, and may also have conveyances, for example, perforated plastic tubing (see cutaway). Adapted from D. Vallero, *Environmental Biotechnology: A Biosystems Approach*. Elsevier Science, 2015; D. A. Vallero, *Hazardous wastes*, In: *Waste: A Handbook for Management*, 2011, p. 393; EPA, EPA/600/R-07/060, *Landfill bioreactor performance: second interim report: outer loop recycling & disposal facility—Louisville, Kentucky*, 2007.

The municipal landfill (see Fig. 12.1) is a common feature of the landscape of cities, small towns, and rural areas. In the United States, the MSW landfills currently in service are regulated under the nonhazardous solid waste program, that is, Subtitle D of the RCRA [3]. As mentioned, however, from a scientific standpoint, MSW could very well contain substantial quantities of hazardous waste, which would find its way to a municipal waste facility.

A landfill is an entire disposal facility in a contiguous geographic space where municipal waste is placed in or on land. The term does not cover land application units, surface impoundments, injection wells, or waste piles. Many MSW landfills receive other types of waste, such as construction and demolition debris, industrial wastes, and sludge [5].

The U.S. criteria for MSW landfill siting and design are [6]:

- Ensuring that landfills are built in suitable geological areas away from faults,

wetlands, flood plains, or other restricted areas.

- Installing a flexible membrane (i.e., geomembrane) overlaying two feet of compacted clay soil lining the bottom and sides of the landfill. They are used to protect groundwater and the underlying soil from leachate releases.
- Installing leachate collection and removal systems atop of the composite liner and removing leachate from the landfill for treatment and disposal.
- Maintain operations for compacting and covering waste frequently with several inches of soil. These practices help reduce odor, control litter, insects, and rodents, and protect public health.
- Testing groundwater wells to determine whether waste materials have escaped from the landfill.
- During and after closure, covering landfills and providing long-term care of closed landfills.

- Controlling and remediating landfill releases and adhering to ground water protection standards.
- Providing funding for environmental protection during and after landfill closure.

Certain materials may be banned from disposal in MSW landfills, such as common household items like paints, cleaners/chemicals, motor oil, batteries, and pesticides. Specified quantities of these household hazardous waste require proper handling, such as household hazardous waste drop-off stations [6].

MSW landfills can also receive household appliances (so-called white goods) that are no longer needed [6]. Many of these appliances, such as refrigerators and air-conditioning units, encapsulate ozone-depleting refrigerants and their substitutes. Thus the waste manager must adhere to the federal disposal procedures for household appliances that use refrigerants to protect the stratospheric ozone layer.

2 DUMPS, TIPS, LANDFILLS, AND SANITARY LANDFILLS

The people of the ever-expanding population of the world seek an improved or improving standard of life that, in turn, demands the acquisition of new goods and the discarding of old. As most of the world's population is urbanized, an ever-increasing volume of MSW is produced, most of which has to be disposed of in what have become known as landfills.

The need for the collection and sanitary disposal of MSW was not recognized until recently. The science and engineering of MSW management is also relatively new. Fifty years ago, throughout the world, most municipal waste was disposed of in open dumps or tips, even by authorities serving very large communities, for example, New York. It was only in the early 1930s that the need for improved methods of MSW disposal started to raise concern in Europe [7, 7a]. In 1959 the first recognized definition of

sanitary landfilling, more or less as we know it now, was published by the American Society of Civil Engineers (ASCE) [8]. The ASCE defined "sanitary landfilling" as a controlled operation in which MSW is deposited in defined layers, each layer being compacted and covered with soil before depositing the next layer. Although very strict regulations relating to sanitary landfilling have been formulated and are now being applied in various parts of the developed world [9, 10], it is also apparent that these new rules have and are being applied mainly to new landfills and that conditions, at many preexisting landfills, fall short of present ideals. It is also inevitable that current "ideal" regulations and practices will become outdated and be regarded as rudimentary and inadequate within the space of a few years. Hence, even in developed countries, the professions concerned with waste disposal are in a constant state of trying to catch up with and introduce the latest trends and regulations. In most developing countries, open dumping remains the most widespread method for disposing of MSW. To the environmentally conscious municipal engineers working in developing countries, the problems of attempting to bring the municipal waste problem under control often appear almost insuperable, yet work must continue in the direction of more efficient collection and transportation and safer and more environmentally acceptable disposal.

What distinguishes a *developing* country from a *developed* one? A formal and succinct definition [11] is that a *developing country* is one where the per capita gross domestic product is lower than the average for the world. Thus a developing country is one where the people are poor, on average. However, there are many countries for which this definition may be inadequate, because industrialized urban areas in a country may be "developed," while country areas are still "developing." It is rare to find wealth evenly distributed within large cities or between town and country. These countries are usually referred to as having *mixed economies* (e.g., China and India).

In an open dump or tip, MSW is deposited in a conveniently situated preexisting excavation (e.g., an abandoned quarry pit), on a convenient piece of unused land or on a convenient hillside. The term “landfilling” arises from the operation of filling a hole, that is, filling to build a “new” land surface, whereas the operation of dumping on a level or sloping surface was originally termed landbuilding. Now, however, the word “landfilling” is used for both types of operation.

The basic difference between a dump or tip and a landfill is that in a dump there is no attempt to separate the waste from the underlying soil or rock strata and where the hole extends to below the groundwater level, waste is dumped directly into the groundwater. As a result, pollution of the groundwater by substances leached from the waste is almost

inevitable, unless (by chance) the underlying soil or rock is highly impervious. There is also no attempt to cover the waste to prevent odors and exclude breeding flies and scavenging birds (e.g., crows) and animals (e.g., rats) or to seal the surface of the dump against the ingress of rain. In contrast, a sanitary landfill is constructed on a sealed impervious base that is covered with a drainage system designed to collect leachate that usually (but not always) emanates from the waste. Each day's deposition is formed into a layer about 2-m thick and is compacted to reduce its volume (and therefore maximize the utilization of space). Each layer is covered at the end of the day to exclude rain, insects, and scavenging birds and animals. The collected leachate is treated to purify it before discharging it into the surface water system. Fig. 12.2 shows sections

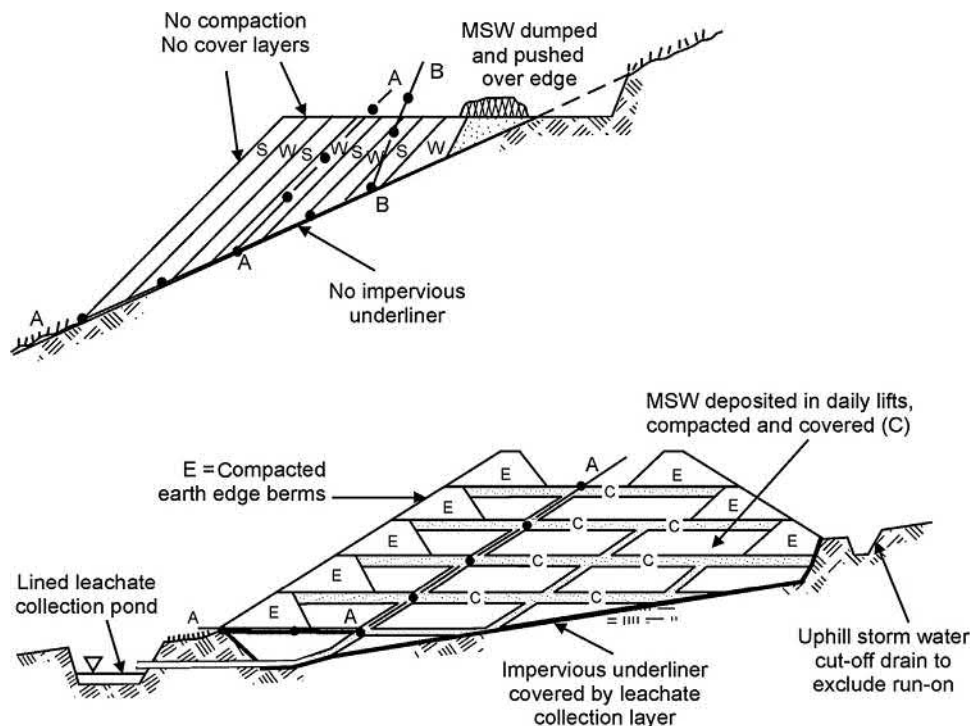


FIG. 12.2 Top: Construction of a MSW dump placed on a hillside. The layers W, S, W, ... indicate differences in the composition of the waste between winter and summer. Bottom: Construction of a sanitary landfill, with MSW compacted and covered to exclude rain, insects, and scavenging birds and mammals.

through a hillside dump and a sanitary landfill to show the differences in their construction.

In summary, the simple but inadequate waste dumps of yesterday are still with us in most of the developing world, whereas the developed world is using the vastly improved sanitary landfill of today while planning and experimenting with and tentatively applying the still more improved landfill technology of tomorrow.

Fig. 12.3 shows a typical layout of the leachate drainage collection system of a sanitary landfill, leading to a leachate and contaminated water collection sump, while Fig. 12.4 shows the construction of a typical impervious underliner, with its leachate collection layers. The leachate collection layers consist of a large-size gravel or crushed rock of 38–50 mm size to reduce the risk of the voids between the rock particles

becoming blocked by chemical gels of iron hydroxide or by bioslimes. The flexible membrane liner or geomembrane usually consists of a 2-mm thick synthetic rubber (neoprene) or plastic (e.g., flexible polypropylene (fPP)) membrane protected from accidental damage by a sand layer above and laid in direct contact with a compacted clay layer. The geomembrane should be completely impervious to seepage of the leachate, but because it has to be constructed by welding a series of sheets together, it is always possible that a seam may leak, in which case the compacted clay liner will prevent the leakage from escaping to the groundwater. There is also a possibility that the clay liner may crack, and for this reason, it rests on a leakage detection and collection layer. This is constructed in defined zones so as to enable the

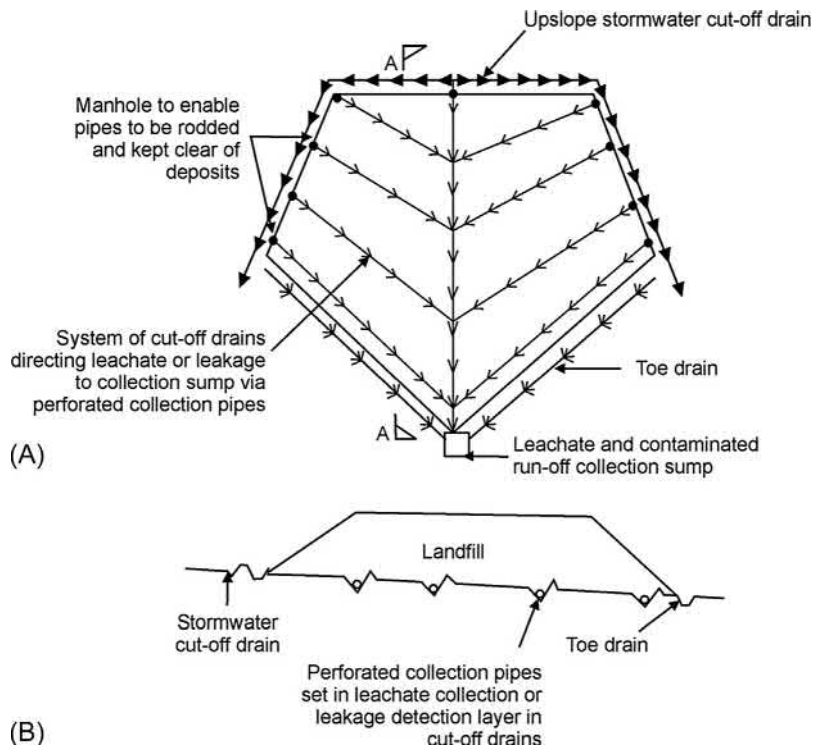


FIG. 12.3 (A) Typical layout in plan of a leachate collection system for a sanitary landfill. (B) Layout in section along line AA.

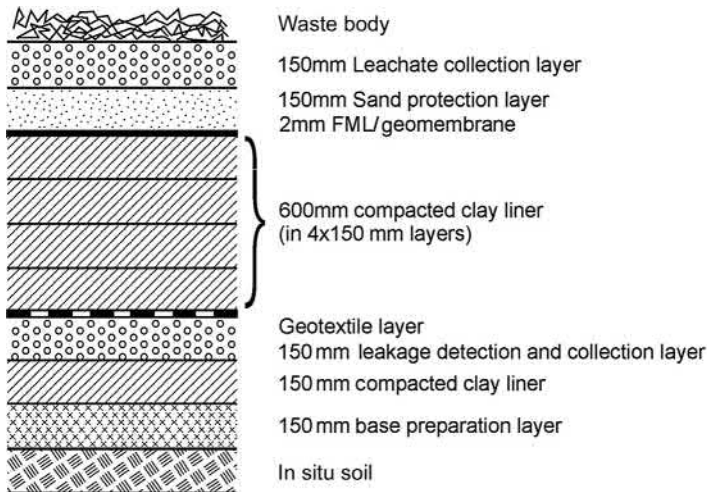


FIG. 12.4 Construction of a typical impervious lining for a sanitary landfill.

position of any leak to be established and if possible repaired, or if not possible isolated, and the leakage separately collected.

3 THE LANDFILL AS A WASTE CONTROL SYSTEM

Research has demonstrated that the rate of microbial degradation of solid wastes in these landfills can be enhanced, especially by increasing the moisture content of the waste. This includes increasing the amount of water in the landfill cells and layer, as well as recirculating leachate [5]. Indeed, as shown in Fig. 12.1, most currently operated landfills collect and treat the leachate, so recirculation systems can be properly designed and operated.

Waste is delivered, principally by trucks, and is progressively stored in a landfill so that the age of the waste between the cells and within the cells (e.g., cells within layers) may vary considerably. Because degradation is a function of time, the biochemical and microbial conversion between and within cells will also vary. Thus the chemical speciation within a landfill varies within two and three dimensions in space. This also means that the age of the waste affects the

amount of oxidation-reduction, pH, and other important environmental conditions within each of the landfill's cells. Therefore both the constituents of the waste and the physical, chemical, and biological condition of the landfill determine the rate of waste degradation.

The different landfill stabilization phases often overlap and can be viewed as to each phase's role within the system. The initial phase results in aerobic decomposition followed by four stages of anaerobic degradation. Thus the majority of landfill decomposition by volume occurs under anaerobic conditions. Generally, biodegradation follows three basic stages [7, 7a, 12, 13]:

1. The organic material in solid phase, as represented by chemical oxygen demand (COD), decays rapidly as larger organic molecules degrade into smaller molecules.
2. These smaller organic molecules in the solid phase undergo dissolution and move to the liquid phase (CODL), with subsequent hydrolysis of these organic molecules.
3. The smaller molecules are transformed and volatilize as CO_2 and CH_4 , with remaining biomass in solid and liquid phases.

During the first two phases, little material volume reaches the leachate. However, the biodegradable organic matter of the waste undergoes a rapid decrease in volume. Meanwhile, the leachate COD accumulates because of excesses of more recalcitrant compounds compared to the more reactive compounds in the leachate.

These three steps can be further grouped into five phases by which degradation occurs in a landfill bioreactor system, as shown in Fig. 12.5. Successful conversion and stabilization of the waste depends on how well microbial populations function in syntrophy, that is, an interaction of different populations to provide each other's nutritional needs.

3.1 Phase I: Initial Adjustment

As the waste is placed in the landfill, the void spaces contain high volumes of molecular oxygen (O_2). With added and compacted wastes, the O_2 content of the landfill bioreactor strata gradually decreases. Microbial populations grow, density increases. Aerobic biodegradation dominates, that is, the primary electron acceptor is O_2 .

3.2 Phase II: Transition

The O_2 is rapidly degraded by the existing microbial populations. The decreasing O_2 leads to less aerobic and more anaerobic conditions in the layers. The primary electron acceptors during

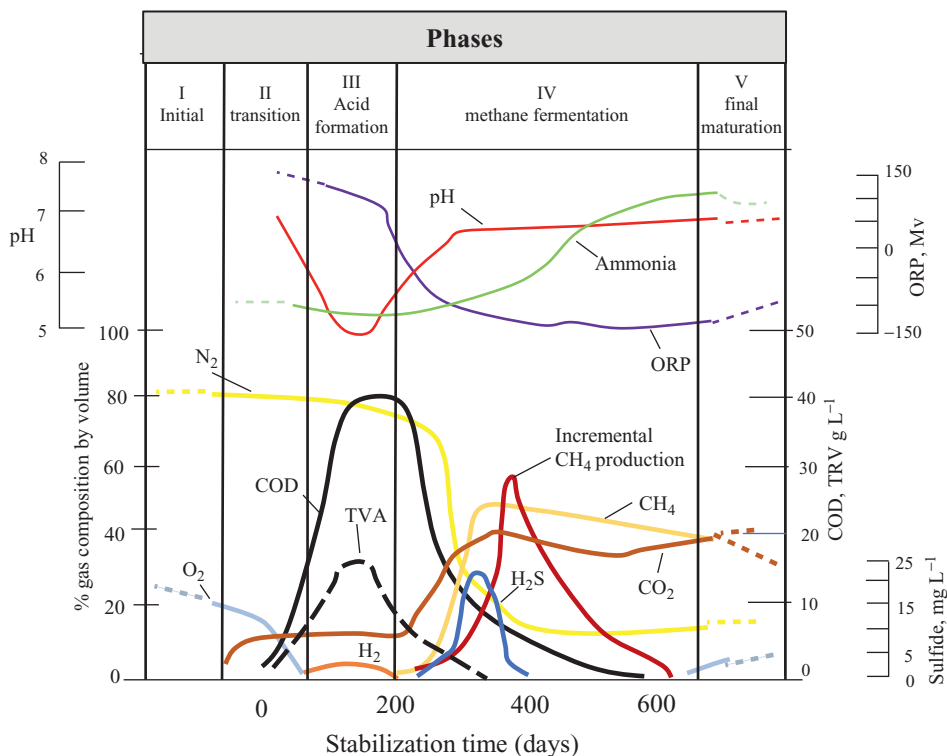


FIG. 12.5 Phases of solid waste decomposition in a landfill, showing changes in released compounds and landfill conditions. Note: COD = chemical oxygen demand; TVA = total volatile acids; and ORP = oxidation-reduction potential. From EPA, EPA/600/R-07/060, Landfill bioreactor performance: second interim report: outer loop recycling & disposal facility—Louisville, Kentucky, 2007.

transition are nitrates and sulfates, since O_2 is rapidly displaced by CO_2 in the effluent gas.

3.3 Phase III: Acid Formation

Hydrolysis of the biodegradable fraction of the solid waste begins in the acid formation phase, which leads to rapid accumulation of volatile fatty acids (VFAs) in the leachate. The increased organic acid content decreases the leachate pH from approximately 7.5–5.6 [8, 14]. During this phase, the decomposition intermediate compounds like the VFAs contribute much COD. Long-chain volatile organic acids (VOAs) are converted to acetic acid ($C_2H_4O_2$), CO_2 , and hydrogen gas (H_2). High concentrations of VFAs increase both the BOD and VOA concentrations, which initiates H_2 production by fermentative bacteria, which stimulates the growth of H_2 -oxidizing bacteria. The H_2 generation phase is relatively short because it is complete by the end of the acid formation phase.

The increase in the biomass of acidogenic bacteria increases the amount of degradation of the waste material and consuming nutrients. Metals, which are generally more water soluble at lower pH, may become more mobile during this phase.

3.4 Phase IV: Methane Fermentation

The acid formation phase intermediary products (e.g., acetic, propionic, and butyric acids) are converted to CH_4 and CO_2 by methanogenic microorganisms. As VFAs are metabolized by the methanogens, the landfill water pH returns to neutrality. The organic strength (i.e., oxygen demand) of the leachate decreases at a rapid rate as gas production increases in correspondence with increases in CH_4 and CO_2 gas production. This is the longest lived waste decomposition phase.

3.5 Phase V: Final Maturation and Stabilization

The rate of microbiological activity slows during the last phase of waste decomposition as the supply of nutrients limits the chemical reactions,

for example, as bioavailable phosphorus becomes increasingly scarce. CH_4 production almost completely disappears, with O_2 and oxidized species gradually reappearing in the gas wells as O_2 permeates downwardly from the troposphere. This transforms the oxidation-reduction potential (ORP) in the leachate toward oxidative processes. The residual organic materials may incrementally be converted to the gas phase, and as organic matter is composted; that is, the organic matter is converted to humic-like compounds (although these processes have not yet been completely scientifically documented within a landfill system).

On-site degradation, such as that which occurs in a landfill, is carried out by different genera of microbes, making the kinetics difficult to predict for any facility. Such microbial populations occur naturally in the landfill (e.g., natural soil bacteria). However, varying temporal and spatial site-specific conditions to achieve optimal performance is often a heuristic process. The kinetics of microorganisms in landfill bioreactors have not been widely investigated; this is probably because these groups of microorganisms are much more difficult than aerobes to culture. Hopefully, the emergence of molecular-based nonculture techniques will increase this information. To date, landfill bioreactor performance has been evaluated and controlled by indirect evidence, for example, waste stabilization is characterized by monitoring the outcome of the decomposition process. For example, recirculation of leachate has been shown to shorten the initial lag phase, even though the microbial species responsible for this accelerated decomposition have not been precisely identified [9, 15].

Bioengineering improvements to a landfill bioreactor require attention to the sensitivity of variables. Finding methods to improve efficiency depends on optimizing microbiological metabolic processes. For example, the amount of leachate to be recirculated affects the quantity of direct inhibition of microbial metabolism, but a response of the microbial population to

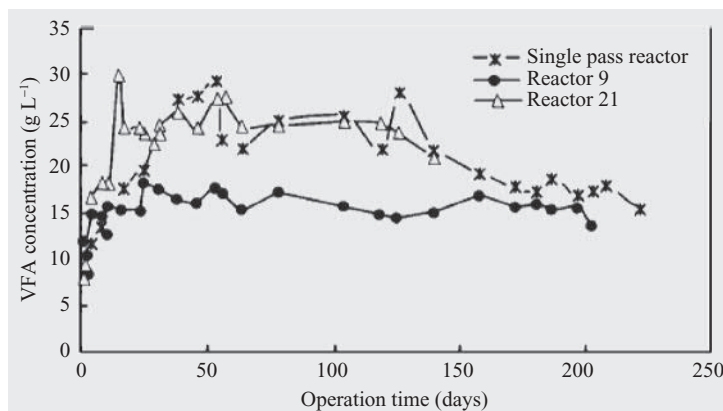


FIG. 12.6 Leachate recirculation and volatile fatty acid (VFA) accumulation compared to VFA generation under conventional landfill management. The leachate in “Reactor 9” was recirculated at 9 L day^{-1} (2.4 gal per day, i.e., 2.4 gpd) = 13% of the reactor volume. The leachate in “Reactor 21” was recirculated at 21 L day^{-1} (5.5 gpd) = 30% of the reactor volume. The VFA buildup in the reactor with a higher leachate recirculation rate of 21 L day^{-1} (5.5 gpd) was nearly as high as the VFAs generated in the single-pass (i.e., conventional) reactor. The 21 L day^{-1} (5.5 gpd) bioreactor experienced a spike of $30,000 \text{ mg(VFA) L}^{-1}$ within 30 days, which can be detrimental to methanogenic bacteria. From D. A. Vallero, *Hazardous Wastes, In: Waste: A Handbook for Management*, 2011, p. 393; EPA, EPA/600/R-07/060, *Landfill bioreactor performance: second interim report: outer loop recycling & disposal facility—Louisville, Kentucky*, 2007.

the lower pH induced by the VFAs. Thus the volume of recirculated leachate must be adjusted to minimize the accumulation of VFAs (see Fig. 12.6).

4 THE LANDFILL AS A SOURCE OF POLLUTION

Landfills are designed both to store and to treat wastes. Much of the potential risk from MSW landfill results from the migration of contaminated leachate and landfill gas (LFG). Thus contamination exists in two phases, liquid and solid, which means that pollutants can be transported off-site by advection and other processes.

In North America, landfill regulations call for a system that minimizes liquid infiltration into the solid waste mass by controlling the amount of moisture allowed into these landfills. These so-called dry tomb landfill designs produce strata within the bioreactor system with low moisture content. While this decreases the amount of leachate, it also severely limits biodegradation, since moisture is a limiting factor for biofilm

production and microbial metabolism [12]. Thus the likelihood of undegraded contaminants increases, as does their associated risk since the exposure integration time is protracted. These exposures include emissions from fugitive dust; combustion from the flare; microbial releases; and the migration of contaminants through soil, ground, and surface waters. Current regulations require leachate and LFG emissions to be monitored for at least 30 years after closure of a landfill site or even longer if there is reason to believe the risks continue after that time [10, 16].

Depending on the stages discussed in the previous section the LFG consists of varying percentages of CH_4 , CO_2 , and other gases (see Fig. 12.7.). As the O_2 concentrations fall, the reduction leads to releases of hydrogen and the microbial population becomes more anaerobic. These anaerobes give off greater amounts of CH_4 , and the CO_2 concentration falls until the near steady-state conditions of about equal amounts of CH_4 and CO_2 , along with less than 5% N_2 . The composition of the gas produced changes with the phases of decomposition.

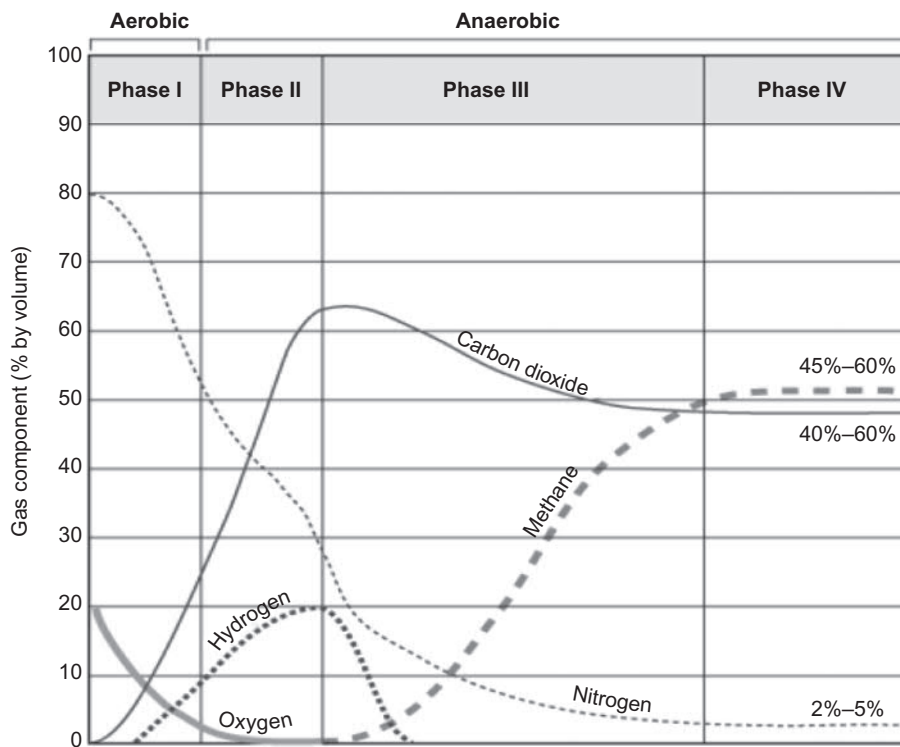


FIG. 12.7 Production of landfill gas during the operation of a municipal waste landfill. Note: phase duration varies with waste type and landfill conditions. From EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills, (2011). Available: <https://www.epa.gov/sites/production/files/2015-12/documents/landfills.pdf>.

For safety reasons, LFG is often collected and burned at larger landfills. It is also collected and used as a fuel for municipal and other operations.

In many parts of the world including countries in Europe, LFG is collected and after separating the CO_2 from the CH_4 , the methane is added to the National Gas grid or used for heating. The overall ratio of methane to carbon dioxide in LFG is usually about 60% CH_4 and 40% CO_2 although the overall LFG production is 50% of each. The reason for the difference is the solubility of CO_2 in the aqueous leachate. Further discussion on LFG can be seen in see Section 6.

Landfills often operate for up to 30 years, which means that waste in a landfill may undergo several phases of decomposition simultaneously. Older waste in one area will decompose at a different rate than recently

buried waste in another area [11, 17]. Because the LFG is substantially composed of greenhouse gases, landfills have become a target for climate change-related actions. Indeed, landfills emit about 22% of the methane emissions in the United States.

Waste management decisions on the type and location of a landfill must adhere to regulatory and design standards, institute monitoring systems that serve to support effective operation and maintenance of the landfill, and tailor needed corrective interventions to previously approved contingency and emergency response plans. This applies to all aspects of the facility, for example, landfill engineering, controls and leachate and air monitoring systems. The planning should be consistent with land use plans and programs promoting pollution prevention,

recycling, and composting. Waste managers may also be called upon to provide technical advice during policy-making. The waste manager must make use of reliable soil, surface water, and ground water data. The U.S. Geological Survey, for example, maintains water resource data bases that support solid and hazardous waste decision making, especially storage capacity, transmissivity, and other aquifer features. Although less abundant, they also gather data on water quality. In addition, environmental data sets, such as those housed by U.S. EPA help to connect potential sources of ground water pollution, for example, landfills and other waste sites, to private and public potable water supplies. [13, 18].

Certainly, other engineered systems beside landfills are employed to address solid waste. However, landfills aptly illustrate many of the abiotic and biotic processes and mechanisms.

Landfills are engineered biosystems, so their efficiency is directly related to microbial metabolism. The amount of leachate that is recirculated, for example, affects the quantity of organic acids. Elevated VFA concentrations inhibits the rate of methanogenesis. This is not

a direct inhibition of microbial metabolism, but a response of the microbial population to the lower pH induced by the VFAs. Thus the volume of recirculated leachate must be adjusted to minimize the accumulation of VFAs (see Fig. 12.6).

5 GENERATION AND CHARACTERISTICS OF MSW

The type and quantity of refuse generated by a community depends on its culture and the per capita income. Wealthy communities form *throw away* societies, whereas poor communities have less to throw away and are more ingenious in reusing, recycling, and refurbishing articles that a wealthier community would discard. The amount of waste produced per head of population varies from as low as $0.05 \text{ kg day}^{-1} \text{ ca}^{-1}$ for the very poor to as much as $2 \text{ kg day}^{-1} \text{ ca}^{-1}$ for the rich (note that here and elsewhere in this chapter, d is the symbol for day and ca is the symbol for capita) [19, 20]. The relationship between wealth and waste is illustrated by Fig. 12.8. The urbanized, very

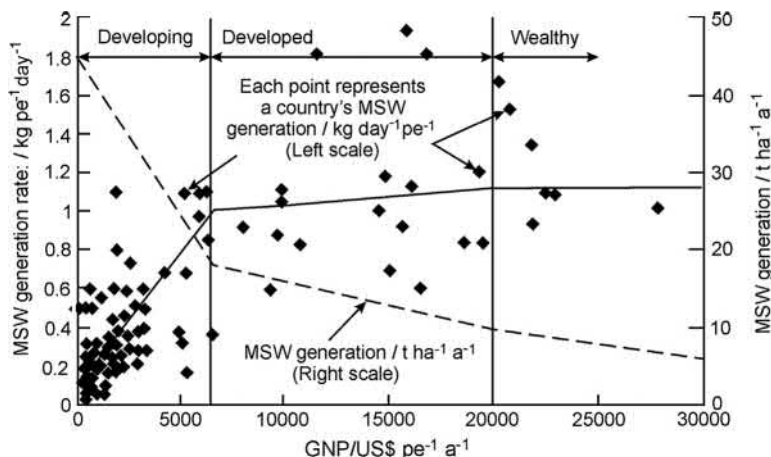


FIG. 12.8 Relationship between rate of generation of municipal solid waste (MSW) as a personal generation rate ($\text{kg day}^{-1} \text{ ca}^{-1}$) and gross national product ($\text{\$ a}^{-1} \text{ ca}^{-1}$) as well as an areal generation rate ($\text{t ha}^{-1} \text{ a}^{-1}$). Here \$ refers to U.S. dollar, ca to capita, d to day, ha to hectare, and a to annum. After D. Vallero, *Environmental Biotechnology: A Biosystems Approach*. Elsevier Science, 2015; D. A. Vallero, *Hazardous Wastes*, In: *Waste: A Handbook for Management*, 2011, p. 393.

poor invariably live in overcrowded conditions, whereas the rich have a generous living space. The net effect is that very poor communities generate about 45t per hectare per annum ($45\text{t ha}^{-1}\text{a}^{-1}$) of MSW, whereas rich communities generate only $10\text{t ha}^{-1}\text{a}^{-1}$ [20]. This is also indicated in Fig. 12.8. A very poor urban area in a developing country measuring, say, $10 \times 10\text{km}$ may generate $450,000\text{t a}^{-1}$ of MSW (note that here and elsewhere in this chapter, a is the symbol for annum, that is, year). As the size of cities, especially in the developing world, is rapidly increasing, the disposal of MSW has become a problem of insuperable proportions in many cities of the developing world, for example, Manila (Philippines) and Jakarta (Indonesia).

Fig. 12.8 enables a rough estimate to be made of the present total annual generation of household waste (i.e., waste generated in either town

or country). If the world's population is taken as 7×10^9 and if most of these people are poor and on average generate only $0.2\text{kg day}^{-1}\text{ca}^{-1}$ the annual global generation of household waste would be $7 \times 10^9 \times 0.2 \times 365\text{kg a}^{-1} = 511 \times 10^9\text{kg a}^{-1}$, or $511 \times 10^6\text{t a}^{-1}$, or say 450×10^6 to $550 \times 10^6\text{t a}^{-1}$. This is quite small (15%) in comparison with the estimated annual quantity of mine waste (see Chapter 3) of up to $35 \times 10^9\text{t a}^{-1}$, but if uncontrolled or poorly controlled, MSW can adversely affect the health, quality of life, and safety of the population to an even greater extent than does mine waste.

Table 12.1 (based on [20] and other sources) presents some of the differences and similarities that may exist in refuse composition between developed and developing countries and mixed economies. The most notable differences between refuse compositions, for developed and developing countries, lie in the percentages

TABLE 12.1 Examples of the Composition (Mass %) and Generation of Municipal Solid Waste in Developed and Developing Countries and Mixed Economies

Composition in % by mass	Developed countries		Developing countries		Mixed economy	
					South Africa	
	United States	United Kingdom	Delhi, India	Wuhan, China	Benoni	Wattville
Vegetable	22	25	47	16	20	9
Paper	34	29	6	2	36	9
Metals	13	8	1	0.5	10	3
Glass	9	10	0.6	0.6	11	12
Textiles	4	3	—	0.6	1	1
Plastic	10	7	0.9	0.5	7	3
Wood	4			1.8		
Dust, ash, and other unidentified material	4	18	44.5	78	15	63
Refuse density/ kg m^{-3} (uncompacted)	100+	150	420	600	170	400
Refuse generation rate/ $\text{t a}^{-1}\text{ca}^{-1}$	0.65	0.65	0.14	0.20	0.58–0.73	0.15

'a' refers to annum.

of paper and plastics (mainly packaging materials, newspapers, etc.). The content of unidentifiable material, ashes, dust, and so on is also characteristically larger in waste from developing communities.

There are also differences between the wastes of developing communities in different parts of the world. The differences in refuse composition between developing countries arise from such factors as culture, climate, differences in fuel, variations in diet, and so on. For example, in Delhi, many people are vegetarians and dung is a common cooking fuel. Relatively little fuel is required for heating. In Wattville (a poor township, by South African standards, south of Benoni in South Africa), coal is commonly used for cooking and heating, and everything that is combustible tends to get burned as fuel. This largely accounts for differences such as those in Table 12.1 in the entries for vegetable matter of 47% for Delhi and only 9% for Wattville. Also, note the differences in refuse generation rates between, say, the United States, Delhi, Wattville, and Benoni (a diverse-populated mining town on the East Rand of South Africa). An affluent community generates 3–5 times as much waste per capita as does a poor community. There are usually also differences in waste composition and volume between summer and winter, with less organic waste arising during winter in temperate climates.

It must also be emphasized that the composition of MSW is not constant with time, but is ever changing as lifestyles evolve. This is illustrated by Fig. 12.9, which shows (a) how the composition of MSW in the United Kingdom evolved in the seven decades from the 1930s to the 1990s [21]. Comparing Fig. 12.9A with Table 12.1 shows that MSW in the United Kingdom during the 1930s to late 1940s was fairly similar in composition to present-day MSW in Wattville. Fig. 12.9B [21] shows how the uncompacted (as collected) density of the United Kingdom's MSW reduced from nearly 300 kg m^{-3} in the

1930s and 1940s to about 150 kg m^{-3} today, mainly as a result of a decreasing ash content and increasing quantities of plastic film, cardboard, and foam packaging.

The generation rate of MSW is an important consideration in the selection of a suitably large disposal site and in the design of landfills, whether the economy is developed, developing, or mixed. Table 12.2, for example, is a design guide for the selection of new landfill sites in South Africa, which takes account of the effects of income and population density on MSW generation.

A landfill being designed to serve a total area comprising suburbs of varying income must take into account variations such as those presented in Table 12.2. The effect of population growth must also be taken into account by escalating the annual tonnages requiring disposal, by the estimated population growth rate, applied as compound escalation.

6 THE GENERATION OF GAS IN LANDFILLED MSW

Once MSW has been deposited on a dump or in a sanitary landfill, it continues to decompose. The products of decomposition are mainly gas (known as landfill gas or LFG) and leachate. In the period shortly after the waste has been landfilled, the pore space is filled mainly with nitrogen and oxygen having much the same proportions as the ambient air. As decomposition of the organic and putrescible components proceeds, the oxygen is very quickly converted by aerobic bacteria to carbon dioxide (CO_2). The gas in the waste passes from an aerobic to an anaerobic state, and anaerobic bacteria start to proliferate and produce methane (CH_4). The effects of these processes are illustrated by Fig. 12.10, which shows the relative volumes of CO_2 and CH_4 in LFG and how they change with time after landfilling in a 50:50 mixture of MSW generated in Benoni and Wattville (see

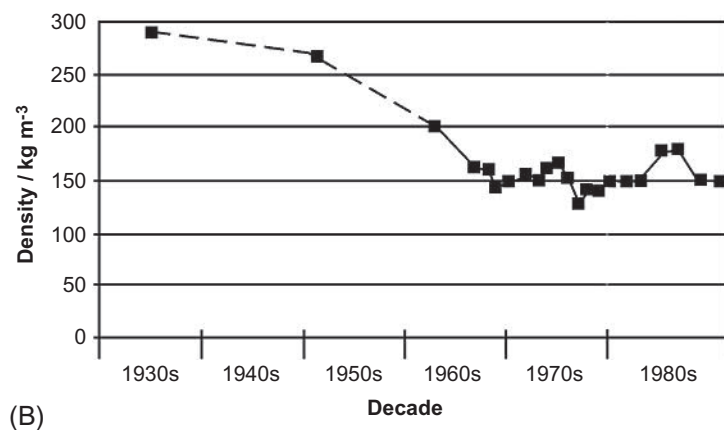
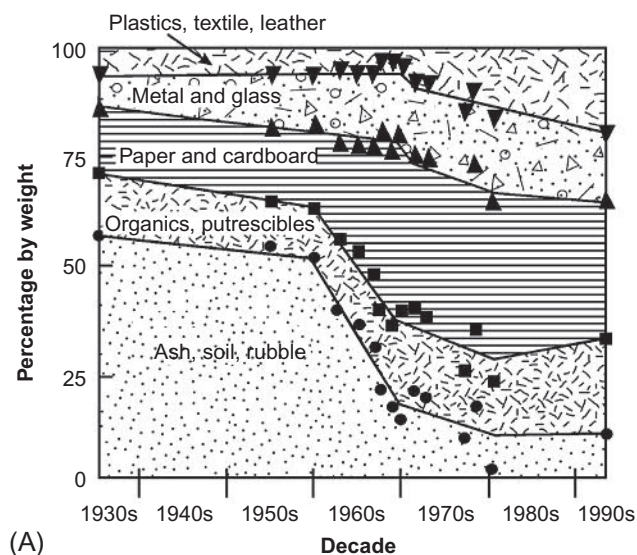


FIG. 12.9 Changes in the composition and collected density of MSW in the United Kingdom from 1935 to 1990. (A) Composition, mass %. (B) Loose (as collected) density.

TABLE 12.2 Design Guide for Refuse Generation in a South African Urban Region of Mixed Economy

Income of community	Population density (ca ha ⁻¹)	Waste density (uncompacted) (kgm ⁻³)	Waste generation rate (ta ⁻¹ ca ⁻¹)	Waste generation (tha ⁻¹ a ⁻¹)
High	18	170	0.58	10
Medium to high	25	200	0.51	13
Low to medium	50	300	0.36	18
Low	200	400	0.22	44
Very low (informal settlements)	300	400	0.15	45

'a' refers to annum and 't' refers to metric tonne, 10³ kg.

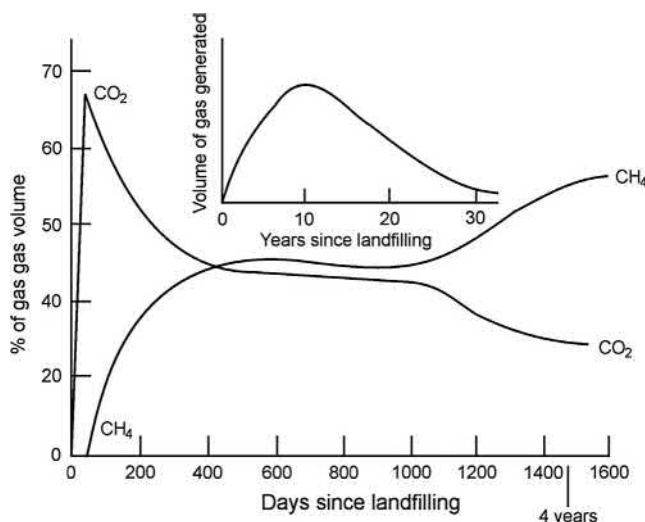


FIG. 12.10 Generation of carbon dioxide, CO₂, and methane, CH₄, in landfilled waste. Variation of relative gas composition by volume with time after landfilling. Inset: Variation of gas quantity generated with time.

Table 12.1). Note the rapidity with which the CO₂ content rises initially, while no CH₄ is produced until the oxygen in the pores of the waste has been converted to CO₂ and the anaerobic bacteria are able to proliferate. The main diagram in Fig. 12.10 shows the composition of the gas. The inset diagram shows (schematically) the duration and quantity of LFG generation, which usually reaches a maximum within the first decade and then declines to a negligible amount after 30 years. The two main gas components, CO₂ and CH₄, do not add up to 100%. The rest of the gas component consists of nitrogen.

The CH₄ in LFG is flammable, and this can be a danger if, for example, the waste is ignited by spontaneous combustion. CH₄ can also explode. A case occurred in South Africa where CH₄ seeped out of an MSW dump and passed along the line of a badly backfilled trench into the basement of a nearby building where it accumulated. An electrical spark caused by switching on the light in the basement set off an explosion that wrecked the building. The LFG can be extracted from the waste by means of vertical gas collector wells or horizontal collector drains and then be used to power internal combustion gas engines to generate electricity. It is, however, more common to burn off the collected CH₄ in a flare, both

as safety and environmental protection measures. Both CO₂ and CH₄ are greenhouse gases and the increase of their concentration in the atmosphere is currently being blamed for global warming. If the global warming potential (GWP) of CO₂ is taken as 1, that of CH₄ has been determined as 25 [22]. When CH₄ is burned, it combines with oxygen to give CO₂ and water ($\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$), thus reducing its GWP from 25 to 1. This is one of the reasons for flaring off the gas.

7 THE GENERATION AND POLLUTION POTENTIAL OF LEACHATE

Leachate arises from squeezing out of the water content of the incoming waste ("squeeze") and from rain that percolates through the cover layers and accumulates in the waste. Landfills in wet climates and those that store large quantities of high water content waste therefore generate more leachate than those in dry climates.

In very dry climates, no leachate may be generated. The covered surfaces of sanitary landfills should be, and usually are, sloped to encourage

rainfall to run off, thus reducing the quantity that seeps into the waste. Water is also lost by evaporation from the landfill surface. Hence, the quantity of leachate, expressed as liters per m^2 (or mm of water), is always less than the rainfall. In climates where evaporation from a free water surface exceeds rainfall, no or very little leachate may be generated. In South Africa, sanitary landfill sites are classified by climate into those where landfills are likely to produce leachate and those that are not. Landfills in areas of high-potential evaporation and low rainfall are not required to be equipped with an impervious underlining. Fig. 12.11 shows the method of classification used in South Africa [7, 7a]. Values for the average annual rainfall and the average annual A-pan evaporation are available for all of the meteorological stations in the country. (An A-pan consists of a shallow galvanized steel pan, 1.8 m in diameter by 0.3 m deep. The pan is filled with water and the water level is measured daily to determine the evaporation, E_A , compensating for any rain, R , that fell during the past day.) The constant of proportionality 0.4 in the equation $R = 0.4\bar{E}_A$ in Fig. 12.11 would vary from climatic area to climatic area on the Earth. As indicated in Fig. 12.11, if a point such as that for

Site A falls below and to the right of the dividing line, leachate is expected to be generated and an underliner is required. If it falls above and to the left, as for Site B, no leachate would be likely and no underliner would be required.

Fig. 12.12 shows examples of leachate generation compared with rainfall in a series of field experiments carried out at Benoni and Wattville, and it also shows the potentially polluting nature of leachate if it should escape from the closed system of landfill—leachate collection layers—leachate treatment and disposal.

The construction of the experimental cells will be described in detail to show the possible effect of size and construction details on the results obtained from field experiments. The experiment comprised two large and two small experimental landfill cells, one of each being filled with waste from Wattville and the other two with waste from Benoni.

The large cells were constructed as part of the prototype landfill. The cells were lined with high-density polyethylene (HDPE) geomembranes covered by a gravel drainage layer draining to an outlet that was closed by a gate valve. This allowed the leachate to be drained off and measured at regular intervals. The cells measured

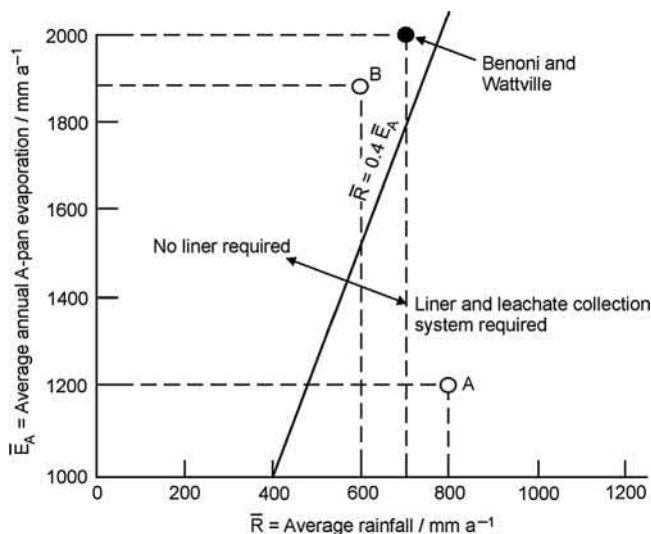


FIG. 12.11 Chart used in South Africa to classify landfill sites by climate. A site plotting at point A would require an underliner and facilities for leachate treatment to be provided. One plotting at B would require no liner, as leachate would not be generated.

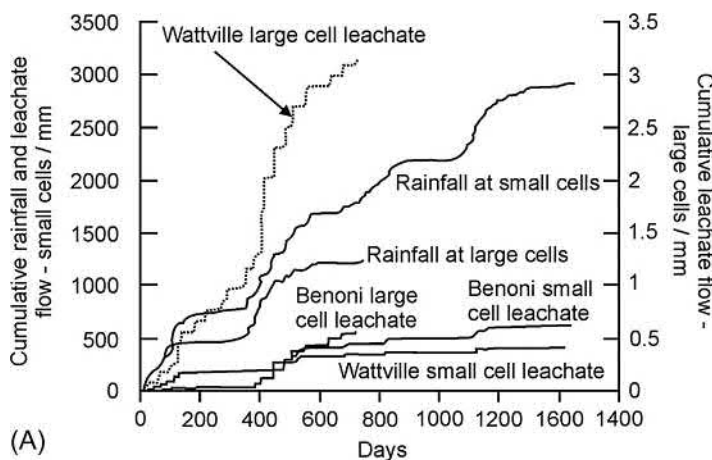
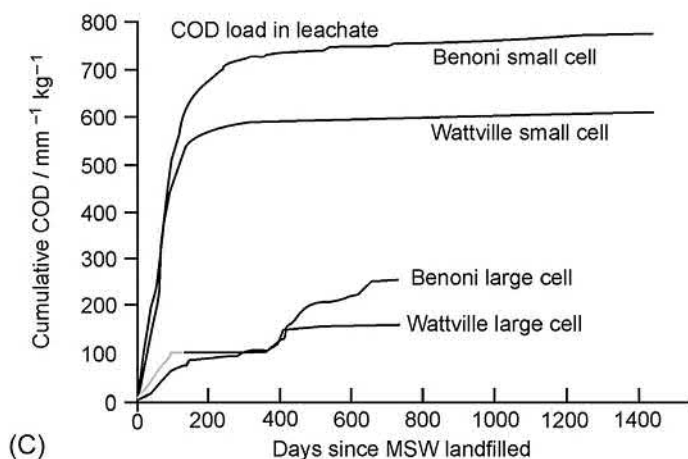
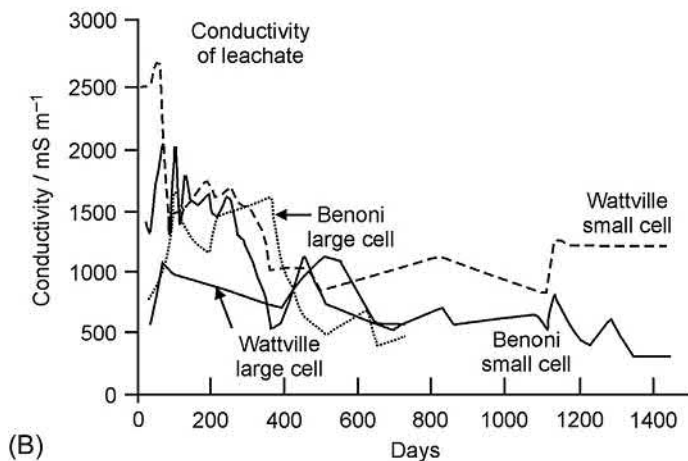


FIG. 12.12 (A) Relationships between rainfall, leachate generated, and time since landfilling for small and large experimental landfill cells. (B) Relationship between conductivity of leachate and time. (C) Relationship between cumulative chemical oxygen demand of leachate and time.



an average of 12×12 m in plan and were 2.5 m deep. The cover layers consisted of a 300-mm layer of the same compacted clayey soil used on the landfill, with a water infiltration rate of 30 mm day^{-1} . The surface of each cell was domed to shed rainfall and further limit infiltration. The small cells were 3.12 m^2 in plan and 1.06 m deep, constructed with vertical brick walls around the cells and with floors sloping to one side, lined with an HDPE geomembrane and covered with a gravel drainage layer. Leachate could be tapped off from each cell via a gate valve. The cover layer on the small cells had an infiltration rate in excess of 200 mm day^{-1} and runoff was prevented by the surrounding brick walls.

Fig. 12.12 shows a selection of results from these tests. At the time, the tests on the small cells had been in progress for 1425 days (3.9 years) and those on the large cells for 740 days (2.0 years).

Fig. 12.12A compares rainfall and leachate production (leachate on the right-hand scale). The cumulative rainfall at the small cells from 725 days onwards (the start of the measurements on the large cells) amounted to 1200 mm, whereas for the large cells it was 1300 mm, hence the two sites had comparable rainfalls. The leachate flow is always much less than the rainfall, as it represents the difference between the rain infiltration and the water that is absorbed by the waste and subsequently partly or completely reevaporated.

Fig. 12.12B shows the variation of the leachate conductivity with time. The conductivity correlates with the total dissolved substances in the leachate and therefore gives an indication of the potential for escaping leachate to pollute groundwater. The diagram shows that the maximum pollution potential exists early in the life of a cell of landfilled waste but declines to a much lower value after about 4 years. This is not to say that after 4 years the leachate is innocuous.

Fig. 12.12C shows how the total quantities of pollutants in the leachate such as chemical oxygen demand (COD, shown here), chloride, ammonia, and nitrates build up rapidly in the first year after landfilling and thereafter grow more slowly. This figure corroborates the data shown in Fig. 12.12B.

Table 12.3 compares some of the results of the study at 725 days after the start of each series of tests.

The comparison shows that the large cells produced very much less leachate than the small cells. This was to be expected because of the differences between the large and small cells (lower cover permeability and larger depth of waste to absorb water). The small cells each produced about the same leachate as a proportion of rainfall, but the large cell of Wattville waste produced much more leachate than the corresponding cell of Benoni waste, probably

TABLE 12.3 Comparison of Results of Small and Large Cell Tests on MSW From Benoni and Wattville at 725 Days After the Start of Each Series

Source of MSW	Cell size	Cumulative rain (mm)	Cumulative leachate (mm)	Leachate/rain (%)	Leachate conductivity (mS m^{-1})	Leachate conductivity Wattville/Benoni	COD load in leachate ($\text{mg mm}^{-1} \text{ kg}^{-1}$)	COD Wattville/Benoni
Wattville	Small	1800	300	17	1000	2	590	0.79
	Large	1200	3.1	0.3	300	0.6	130	0.5
Benoni	Small	1800	400	22	500	—	750	—
	Large	1200	0.6	0.05	500	—	260	—

Note that the units for COD refer to milligrams per millimeter height of water with a surface area of $1 \text{ m}^2 \text{ kg}^{-1}$ dry waste.

because of its lesser capacity to absorb and store water.

Judging by the large cells, the Wattville waste, with its lower organic and higher inorganic contents (Table 12.1), produced leachate with a lower conductivity and COD than did the Benoni waste. The two wastes produced almost the same loads of ammonia and chloride and overall produced leachates with much the same pollution potential. Hence, this experiment seems to show that the pollution potential of landfilled MSW is relatively little affected by quite large differences in waste composition.

The fact that the leachate to rainfall ratios in the large and small tests was so different, although the rainfall was similar, points to the obvious conclusion that field experiments must represent a prototype situation very closely if they are to give results representative of field conditions.

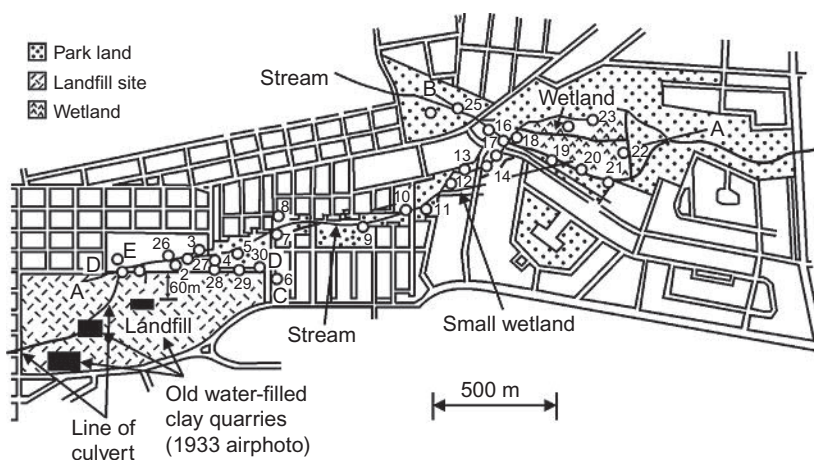
The average annual A-pan evaporation and rainfall for Benoni and Wattville plot is as shown on the climatic classification diagram in Fig. 12.11, and one would therefore expect little or no leachate to be produced from a landfill in this area. The maximum leachate flow of 3 mm in 2 years is only 10% of the expected leakage rate from a geomembrane with welded seams [23] and is therefore acceptable without the need for an underliner.

Finally, the question arises of to what distances downstream and for how long an unlined landfill emitting leachate into groundwater will continue to cause pollution. If groundwater pollution occurs, is it a short-term transient problem or does it persist? Figure 12.13 provides an illustrative example.

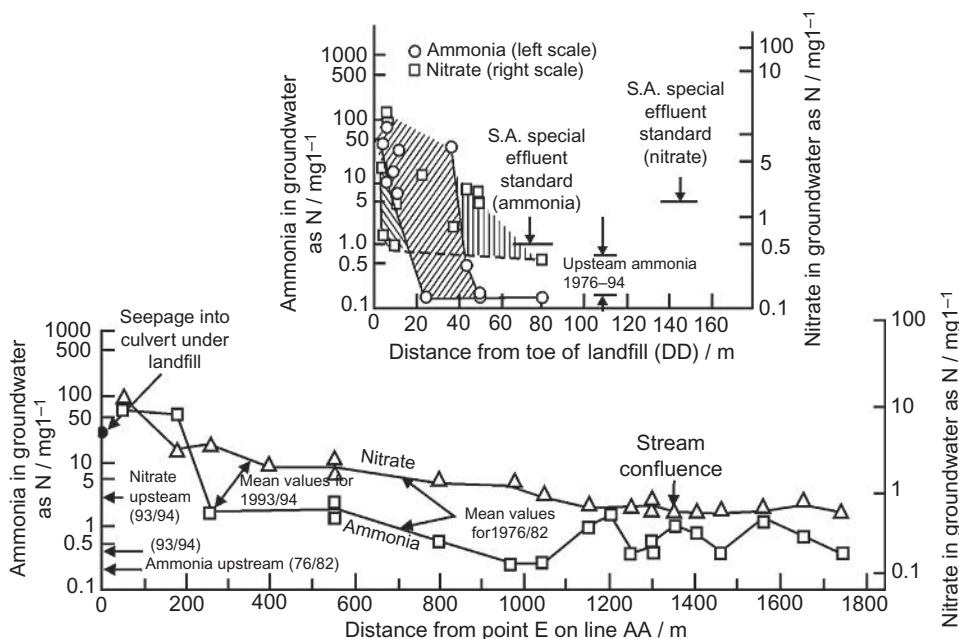
Three clay pits, used for brick making, were closed in 1906 because of the ingress of groundwater. In 1928, the water-filled pits were filled by tipping MSW into them, and the leveled site was then used for an above surface MSW dump. In the late 1960s, the dump was converted to a sanitary landfill which was finally closed in 1978. Fig. 12.13A shows the areas eventually

covered by the landfill, as well as the positions of the original clay pits. In 1976, Ball [24] started a project to establish the pollution status of the landfill, taking groundwater samples by hand augering 1.5-m deep holes at intervals along the banks of the stream that originates upstream of the landfill, passes under the 1960's landfill in a concrete culvert, and flows down the valley downstream of the landfill. The 30 sampling positions are marked in Fig. 12.13A. In 1976/1977, a 1.2-m diameter hole was augered through the landfill. Samples taken from the hole showed that the post-1960's sanitary landfill had been separated from the underlying waste dump by a 2.5-m thick layer of compacted soil. The landfill is located in a climatic area for which the A-pan evaporation and rainfall are very similar to those of Benoni-Wattville and therefore does not generate leachate. Samples from the underlying soil confirmed this by showing it to be quite unpolluted. Hence, if any pollution was to be found, it must have originated from the waste deposited prior to the 1960s. The groundwater samples from close to the toe of the landfill showed levels of pollution, relative to the then current South African standards for surface and groundwater quality that slightly exceeded allowable values. The groundwater sampling was repeated in 1993/1994 [25]. The two sets of measurements, taken 17 years apart, gave almost identical results, as can be seen from Fig. 12.13B in which most of the pairs of measurements coincide, except for a few where two points appear at the same horizontal distance from Point E (e.g., at 560 and 1300 m). The more detailed inset in Fig. 12.13B showed that unacceptable values of ammonia persisted to a distance along the stream of 50–80 m from the toe of the landfill and much the same applied to conductivity and COD.

This study and other work [26] show that pollution plumes from landfills may not progress very far from the source, but they may persist for many years, in this case for more than 30 years.



Plan showing landfill, stream and groundwater sampling holes (numbered 1 – 30)



Summary of measurements of ammonia and nitrate in groundwater for 1976 (see (a), line AA / m)

FIG. 12.13 Extent and duration of groundwater pollution by leachate from old landfill.

8 THE SAFETY AND STABILITY OF DUMPS AND LANDFILLS

Mention was made in see [Section 3](#) of some of the dangers posed by LFG, namely, fires and explosions. There is also a danger of a person,

usually a scavenger, in a developing country drowning in CH_4 or CO_2 if they fall asleep in a hollow, possibly kept clear of gas by the wind in the day, that then fills with gas when the wind drops at night. This also happens on coal waste

dumps, and a number of people die in this way each year.

Dumps and landfills are also dangerous because of items such as broken glass and sharp metal objects, for example, pieces of razor wire, and so on, that may be, and often are, mixed up with the MSW. Landfill compactors, trucks dumping waste, and dozers leveling waste are also extremely dangerous to persons working or scavenging on the dump or landfill. Scavengers and workers on landfills are also prone to fungal skin and lung diseases picked up by handling the waste with bare hands and from spores in dust.

Stability of the dump or landfill as a whole also represents a danger. MSW dumps and landfills can be every bit as dangerous as tailings storages. Dumps, especially hillside dumps, may fail by sliding of a wedge of dumped waste such as those defined in Fig. 12.2A and B by surfaces AAA or BBAA. Between 1977 and 1997, seven major failures of MSW dumps and landfills occurred worldwide [27]. Of these, four slides occurred in uncompacted waste dumps in developing countries and three took place in supposedly carefully engineered and operated sanitary landfills, one each in Colombia, South Africa, and the United States of America [28]. The last was reputed (before the failure) to be the biggest and best operated sanitary landfill on the Earth. No lives were lost in the failures of the three sanitary landfills and one of the dumps. In failures of dumps in Turkey, Philippines, and Indonesia between 1993 and 2007, at least 39,278 confirmed and 350 missing and at least 147 deaths occurred, respectively, a minimum total of 464.

The following is a brief description of the disaster with the highest death toll, the slide at Quezon City, Manila, Philippines in 2000 [27], in which between 278 and 628 died.

By the year 2000, the dump covered an area of 12.7ha and was 18–30m high. Incoming waste was dumped on the top of the existing MSW fill and, after being picked over by informal scavengers, was bulldozed over the tipping edge to

form a face at the angle of repose. The surface of the ground on which the dump had been formed, sloped gently at about 2° away from the dump. In late 1999, the contractor operating the dump began to bulldoze waste from the center of the top of the dump toward and over the edges with the result that a basin was created on the top and the slopes around the edges were covered with freshly deposited MSW at its angle of repose.

In the 10 days preceding the failure, exceptionally heavy rain, amounting to 750mm, fell in the Payatas area and reportedly created a lake of storm water in the basin on top of the dump. The contractor cut a deep trench to drain the lake and allow the water to run down the steep outer dump slopes. At some time earlier, a 2–3-m deep open trench had been cut along the toe of the face to intercept the streams of leachate running from it. The waste was also burning in places. What made the situation particularly dangerous was that large numbers of informal scavengers, working on the dump, had established their makeshift shack homes right at the toe of the waste slope. The failure began at 04.30h on 10 July 2000 when loud cracking noises were reportedly heard coming from the waste body. The slide occurred 3h later when an estimated $9\text{--}10 \times 10^3 \text{ m}^3$ of waste slid forward, burying or destroying all the shack homes in its path. The waste does not, however, appear to have liquefied as it only moved forward a relatively short distance and the failure has the appearance of a translational wedge failure of the freshly tipped MSW, similar to that outlined in Fig. 12.12A.

Fig. 12.14 is an aerial view of the dump after the failure. At the toe of the dump, to the right of the failure, a large area of shack homes can be seen. This area extended further to the left, and houses in the extension were deeply buried by the wedge of sliding waste. The burying of these houses was the cause of the enormous death toll. Fifty-eight people were rescued, and after weeks of searching and digging, 278

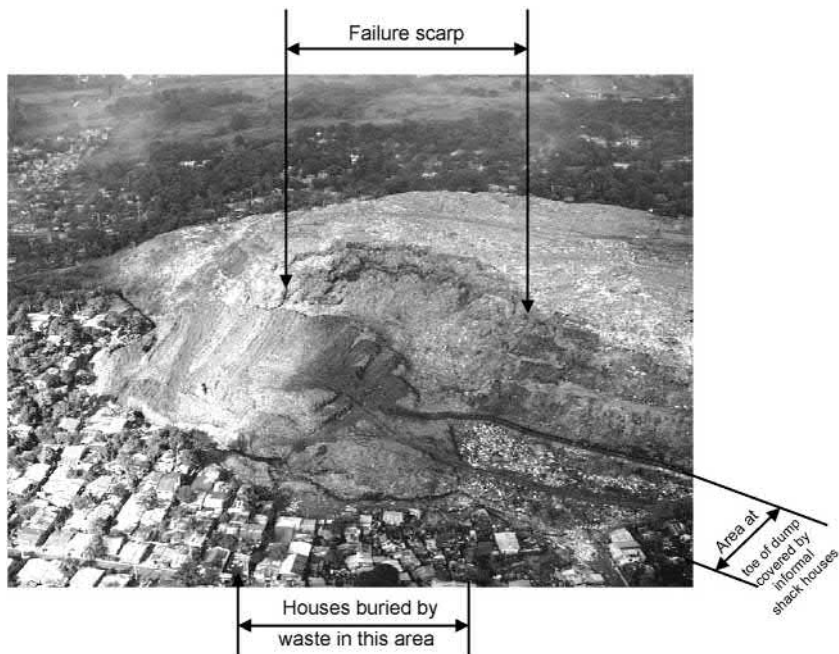


FIG. 12.14 View of failure of Payatas waste dump at Quezon City, Manila, Philippines, in 2000. A strip of shack homes at the toe of the dump was buried by the failure. *Photo provided by Professor Manassero.*

bodies had been recovered, leaving between 80 and 350 missing, believed dead. Thus the death toll may have exceeded 600. The smoldering waste, exposed to oxygen by the slide, started to burn, adding to the difficulties of would-be rescue workers.

9 CONCLUSIONS

The landfill is a proverbial workhorse in storing and treating MSW. It provides excellent rates of biodegradation if sited, designed, and operated properly, but can be source of pollutants, especially from leachate and LFG releases.

Uncompacted, uncovered dumps of MSW should be the landfills of yesterday. Unfortunately, they are still with us today, and in developing countries they are all too often the only

form of MSW disposal in use. Even though it is 50 years since the concept of the compacted, covered sanitary landfill was introduced and formalized, it remains the landfill of the distant future over much of the Earth. In Europe and North America, tomorrow's forms of sanitary landfill are being introduced. In the bioreactor landfill, for example, leachate is recirculated through the waste to accelerate the rate of decomposition. Increasingly, separation of recyclable materials at source is reducing the quantities of waste being landfilled and changing the composition of the waste. [Unfortunately, one of the major landfill failures (mentioned before) in Colombia was being operated as a bioreactor landfill when it failed, to some extent because the operators did not appreciate that increasing the liquid content of the waste would drastically decrease the stability of the landfill.]

In Europe and China, more and more MSW is being used as refuse-derived fuel (RDF) for the thermal generation of electricity. Another option is to compost the organic content of MSW and recycle the paper, plastic, and glass contents. This requires separation at source by the householder. This is very feasible, as schemes of this sort are in successful operation in North and South America, Europe, Australia, New Zealand, and South Africa. Another option is to convert the organic fraction of MSW to liquid biodiesel that can be used to power heavy transport or agricultural tractors. Thus the sanitary landfill and the MSW of the future should have much reduced organic contents, and landfills should therefore generate less LFG and (possibly) a less polluting leachate. Unfortunately, some residues will always remain, (e.g., the ash from RDF fuelled power stations) and hence the landfill will probably always be with us. It is our challenge to make the landfills of tomorrow much better, safer, and less polluting than those of today.

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Wastewater

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OUTLINE

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1 INTRODUCTION

Depending on the specific topic, waste management requires at least a modicum of understanding of wastewater. Arguably, the principal concern for waste managers is to minimize damage to air and water in whatever they do to handle solid waste or waste in any physical form. An understanding of wastewater must be part of the comprehensive and systematic waste management approach of this book. We would

be remiss, within this systems perspective, not to address wastewater here (and air in [Chapter 24](#)). This is particularly important since many of techniques for addressing wastewater also apply to other wastestreams, especially environmental biotechnology for treating hazardous wastes, which will be addressed in more detail in [Chapter 31](#).

The environmental engineer understands that whatever the design, at some point in time and space, water needs to be protected. The

performance specifications during the active life and following closure of a waste site or landfill always include water protection. This may translate into limits on what and how much can leach into groundwater; what may be allowed to flow directly into a stream; or what should be allowed to flow indirectly onto soil, percolate as soil water, and eventually reach the water as a non-point source. These and countless other waste management scenarios include wastewater in one or more of the stages of design, operation, and decommissioning of waste facilities.

1.1 Treatment Rationales

In the United States, water is treated for two basic reasons, water bodies and drinking water. Another way to view this distinction is that the Clean Water Act [1] is mainly concerned with addressing “dirty water” and the Safe Drinking Water Act is mainly concerned that “clean water” is delivered to the human population [2]. The Clean Water Act focuses on cleaning up impaired water bodies, for example, limits on the amounts and types of materials that can be discharged in to streams and other surface waters. The focus of the Safe Drinking Water Act is on the amount of specified chemical and biological substances that can be in a public water supply, that is, maximum contaminant levels (MCLs) [3]. Thus wastewater is the direct focus of the Clean Water Act and the indirect focus on the Safe Drinking Water Act.

2 WATER POLLUTION

Wastewater can contain substances that are highly toxic to aquatic life and human populations. The pollutants may be dissolved or suspended in the water. Thus wastewater can either directly enter surface waters, such as through an outfall structure, or reach a storm sewer system. Once the polluted water reaches the surface water or groundwater, it harms both in many ways. The suspended matter will

increase turbidity, diminishing light infiltration and change the microbial populations in the receiving waters. As is always true in environmental systems, the effects are not limited to a single change. The reduction of light can also substantially diminish the growth capacity of aquatic plants and disrupts normal processes, such as seasonal turnover and nutrient cycling in the surface waters.

Toxic contaminants, both organic and inorganic are carried by suspended particles and dissolved in the water, increasing the organic load and transporting hazardous chemical compounds. Laws and regulations prescribe which substances should be measured in public waters. In the United States, the EPA sets rules on which biological and chemical need to be measured and the methods needed to test them [4]. For the specific procedures for conducting these tests, the waste manager should consult the EPA website, “Clean Water Act Analytical Methods” [5].

2.1 Biological Agents

A primary concern of water is whether it carries pathogenic microbes. When wastewater contains these organisms, they may reach drinking water supplies, recreation facilities, and other places where people may be exposed. They may also enter the food chain, where they can reside at various trophic levels and remain in reservoirs, for example, in fish, that are consumed. Table 13.1 presents some of the methods used to determine the extent of microbial contamination of waters.

2.2 Inorganic Substances

Wastewater and sludge contain almost every element in the periodic chart. These exist in many forms. Chemists differentiate compounds as either organic or inorganic. If a compound lacks a carbon atom that is covalently bonded to another carbon or hydrogen atom, it is classified as “inorganic.” Inorganics are often further differentiated as metals and nonmetals.

TABLE 13.1 Biological Methods for Wastewater and Sewage Sludge

Parameter	Method
1. Coliform (fecal), number per 100mL or number per gram dry weight	Most probable number (MPN), 5-tube, 3-dilution, or Multiple tube/multiple well, or Membrane filter (MF), single step
2. Coliform (fecal) in presence of chlorine, number per 100mL	MPN, 5-tube, 3-dilution, or MF, single step
3. Coliform (total), number per 100mL	MPN, 5-tube, 3-dilution, or MF ² , single step or two step
4. Coliform (total), in presence of chlorine, number per 100mL	MPN, 5-tube, 3-dilution, or MF with enrichment
5. <i>E. coli</i> , number per 100mL ^a	MPN multiple tube, or Multiple tube/multiple well, or MF single step
6. Fecal streptococci, number per 100mL	MPN, 5-tube, 3-dilution, or MF, or Plate count
7. Enterococci, number per 100mL	MPN, 5-tube, 3-dilution, or MPN, multiple tube/multiple well, or MF single step or Plate count
8. <i>Salmonella</i> number per gram dry weight	MPN multiple tube
9. Toxicity, acute, fresh water organisms, LC ₅₀ , percent effluent	<i>Ceriodaphnia dubia</i> acute <i>Daphnia pulex</i> and <i>Daphnia magna</i> acute Fathead Minnow, <i>Pimephales promelas</i> , and Bannerfin shiner, <i>Cyprinella leedsi</i> , acute Rainbow Trout, <i>Oncorhynchus mykiss</i> , and brook trout, <i>Salvelinus fontinalis</i> , acute
10. Toxicity, acute, estuarine and marine organisms of the Atlantic Ocean and Gulf of Mexico, LC ₅₀ , percent effluent	Mysid, <i>Mysidopsis bahia</i> , acute Sheepshead Minnow, <i>Cyprinodon variegatus</i> , acute Siverside, <i>Menidia beryllina</i> , <i>Menidia</i> , and <i>Menidia peninsulae</i> , acute

Continued

TABLE 13.1 Biological Methods for Wastewater and Sewage Sludge—cont'd

Parameter	Method
11. Toxicity, chronic, fresh water organisms, NOEC or IC ₂₅ , percent effluent	Fathead minnow, <i>P. promelas</i> , larval survival and growth Fathead minnow, <i>P. promelas</i> , embryo-larval survival and teratogenicity Daphnia, <i>C. dubia</i> , survival and reproduction Green alga, <i>Selenastrum capricornutum</i> , growth
12. Toxicity, chronic, estuarine and marine organisms of the Atlantic Ocean and Gulf of Mexico, NOEC or IC ₂₅ , percent effluent	Sheepshead minnow, <i>C. variegatus</i> , larval survival and growth Sheepshead minnow, <i>C. variegatus</i> , embryo-larval survival and teratogenicity Inland silverside, <i>Menidia beryllina</i> , larval survival and growth Mysid, <i>M. bahia</i> , survival, growth, and fecundity Sea urchin, <i>Arbacia punctulata</i> , fertilization

^aApproved by the U.S. EPA for enumeration of target organism in wastewater effluent.

Notes: When the membrane filter (MF) method has been used previously to test waters with high turbidity, large numbers of noncoliform bacteria, or samples that may contain organisms stressed by chlorine, a parallel test should be conducted with a multiple-tube technique to demonstrate applicability and comparability of results.

U.S. Environmental Protection Agency, "Identification of test procedures," in 40 CFR 136.3, 2017.

Numerous methods are available for testing the inorganic features of wastewater [4]. These include acidity, ammonia, boron, bromide, calcium, chloride, cyanide, fluoride, nitrogen, nitrate-nitrite, phosphorus, potassium, silica, sodium, sulfate, sulfite, sulfides, and acid mine drainage. The methods for nonmetal detection vary widely, including titrimetric, ion chromatography, ion selective electrode, amperometric, spectrophotometric, digestion, distillation, and colorimetric.

The principal metals, metalloids, and their compounds that often measured in wastewater and receiving waters include aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium VI, and total, cobalt, copper, gold, iridium, iron, lead, magnesium, manganese, mercury, molybdenum, nickel, palladium, platinum, rhodium, ruthenium, selenium, silver, thallium, tin, titanium, vanadium, and zinc. Some of the methods for analyzing metals

include atomic absorption and inductively coupled plasma.

Other measured parameters include acidity, color, hardness, hydrogen ion, specific conductance (indication of dissolved solids), temperature, turbidity, and even some parameters that are chemically organic, for example, surfactants, oil, and grease.

2.3 Organic Substances

The U.S. organic compounds of concern in water as to whether they are pesticide ingredients [4]. The nonpesticide organics include those with widely ranging properties, including aqueous solubility and vapor pressure. This is because solubility is not the only and not necessarily the most important property for predicting the concentrations of organic compounds in wastewater and receiving waters. Recall that wastewater almost always has a high

concentration of suspended solids and even highly hydrophobic compounds will sorb to these particles. The water may also be mixed with other solvents that allow for cosolvation; the process in which a substance is first dissolved in one solvent and then that solution is mixed with another solvent. This means that even a hydrophobic compound in wastewater can mix with the receiving water flow. For example, a dense nonaqueous phase liquid (DNAPL) like chlorinated benzene can migrate into and move within water bodies when it is first dissolved in an alcohol or an organic solvent that mixes with water (e.g., benzene or toluene). This may be particularly problematic for soils and groundwater, since the “D” in DNAPL means this substance is denser than water. Thus particularly if the organic solvent dissipates, the DNAPL will migrate downward in the soil water and groundwater because it has undergone cosolvation with the water. Likewise, the ordinarily lipophilic compound can be transported in the vadose zone or upper part of the zone of saturation where it undergoes cosolvation with water and a light nonaqueous phase liquid (LNAPL), for example, toluene. That is, the LNAPL can be the cosolvent with water, which allows other DNAPLs and LNAPLs to move away from the wastewater source.

Since wastewater is a mixture, its constituents will partition within an environmental compartment at different rates. Processes like sorption and cosolvation increase the ease with which a dense substance that moves toward the bottom of the aquifer in with time may partition between lighter and denser constituents. The lighter constituents will be more likely to migrate upward and could become air pollutants via volatilization than the denser constituents of the mixture, which will likely remain below the surface. However, this should be considered along with other inherent properties and environmental conditions. Of course, some constituents may resist dissolution and continue to migrate downwardly. Therefore partitioning

coefficients like K_{ow} must be applied to each constituent and that partitioning is highly specific to the mixture and to environmental conditions [6, 7].

3 WASTEWATER TREATMENT

The most common conception of the word “waste,” at least for environmental engineers, is solid waste. However, solid waste management often includes the identical or slightly modified versions of the wastewater technologies. Wastewater treatment involves physics, chemistry, and biology, that is, biodynamism. The type of wastewater treatment needed depends on the type of waste and the desired water quality after treatment. For example, the earliest stages of wastewater treatment are physical, that is, removing solids, such as by settling. The next stages also include physics, but also chemistry and biology, in order to understand the transforming of wastewater into higher quality water.

Most municipal wastewater is treated by the screening of materials, sedimentation, and by a secondary treatment (see Fig. 13.1). Sedimentation removes the denser solids. Secondary treatment is usually biological, that is, environmental biotechnology, such as activated sludge or trickling filter. Often, these steps are followed by another, that is, tertiary treatment, which may include disinfection, nutrient removal, or additional solids removal beyond the sedimentation step [8].

The hazards in wastewaters can be direct, owing to its biological or chemical components, for example, pathogenic bacteria and heavy metals, respectively. The hazard may also be more indirect, such as the amount and types of solids and organic substances, which may induce problems like eutrophication of lakes or depletion of oxygen by enhancing the growth of otherwise nonpathogenic bacteria. Sometimes the contaminant can be both directly and

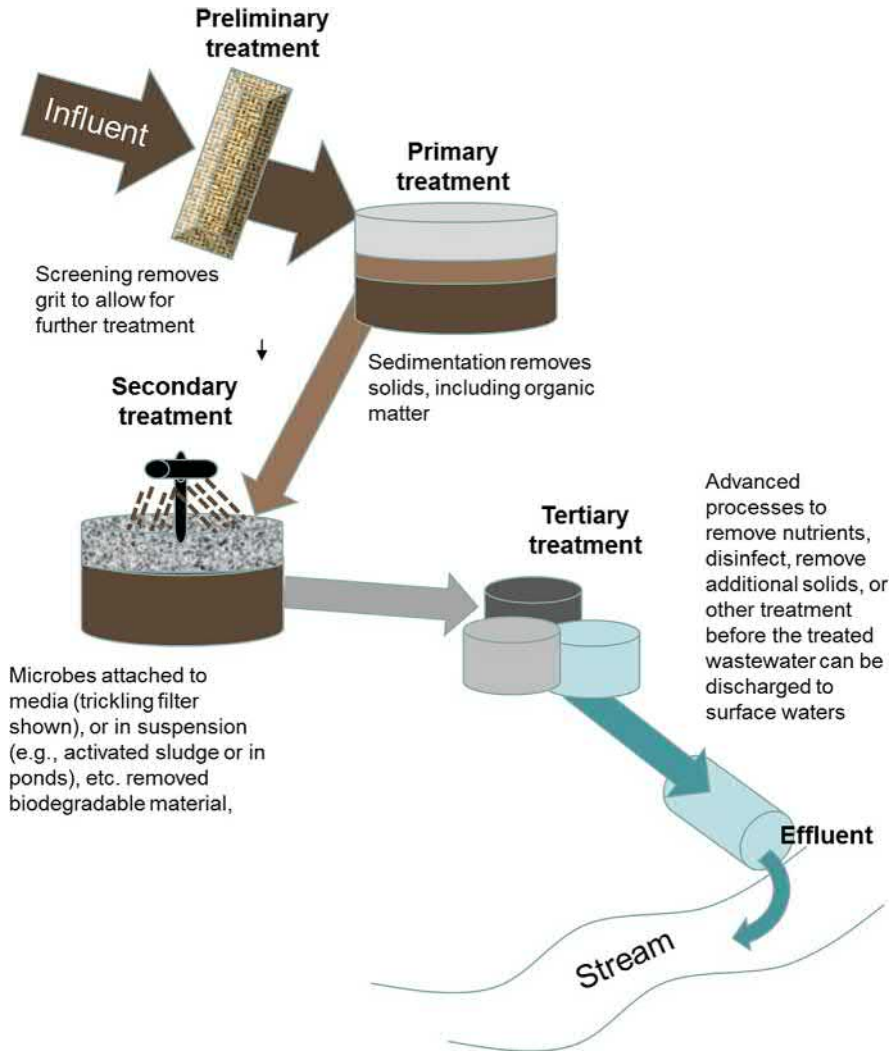


FIG. 13.1 Prototypical wastewater treatment flowchart.

indirectly hazardous, for example, ammonia that kills fish directly or serves as a source of nitrogen that induces microbial growth, leading to eutrophication.

Many of the same parameters important to solid waste managers are used in measuring and treating wastewater. These include solids, biochemical oxygen demand (BOD), fecal coliform, and xenobiotic chemicals.

3.1 Solids Removal

Solid waste and wastewater are relative terms that depend on a gradient of water content. Wastewater has a much higher water content than sludge, which in turn has a higher water content than most landfill wastes. Conversely, wastewater has the lowest solids content. Solids harm surface waters by loading with organic

matter and with toxic substances either sorbed to the suspended solids or as dissolved solids. Thus wastewater's solids content must be measured to meet national, provincial, state, and/or local permit requirements. Solids also indicate the efficiency of process controls. For example, the percent of total solids (TS) indicates how much dewatering of sludge is needed before handling. An effluent permit may limit the percent of total suspended solids (TSS) that may be discharged to a stream. A wastewater treatment plant operator may measure the percent of total volatile solids (TVS) and total volatile suspended solids (TVSS) to indicate how well a digester or trickling filter is operating or to indicate proper food-to-mass (F:M) ratio loading rates for activated sludge treatment [9].

Wastewater solids are classified by size and mass. Total solids include, in descending size order, dissolved, suspended, or settleable solids. Solids content in wastewater is determined by evaporating the water and weighing the residue. In the case of TS, a known volume of the unfiltered water is heated at 103–105°C for 1 h [10]. The TS sample can then be filtered and evaporated to find the total dissolved solids (TDS) and TSS, that is, the solids that pass through the filter are TDS, and the solids that remain in and on the filter are TSS. These are further differentiated as fixed versus volatile solids. Fixed solids are those that remain after igniting the residue from TS. Volatile solids are those that are driven off by ignition. The actual oven and ignition temperatures, filter pore size and type, and other conditions are specified by governmental methods, for example, Method 1684 [10], or standards handbooks, especially *Standard Methods for the Examination of Water and Wastewater* [11].

Removal of solids is realized by physical processes, especially gravity, that is, denser particles settle. Chemical processes also aid in solids removal, such as adding chemical compounds that encourage smaller, lighter particles and colloids to aggregate and precipitate. Finally, biological processes are involved in solids

removal. As mentioned, secondary treatment involves microbial degradation of organic matter. Engineering systems designed to achieve these processes are discussed in Chapter 31. These include activated sludge, aerated lagoons, and biofilters.

3.2 Decreasing Oxygen Demand

The increased input of nitrogen, phosphorus, and other nutrients encourages the growth of algae, leading to algal blooms. When these algae die, they fall to the lake bottom. As they continue to decompose, more oxygen is demanded by the bacteria and abiotic processes, so the concentrations of dissolved oxygen (DO) decline. As a result, fish and other organisms at higher trophic levels in the food chain are stressed. This can result in fish kills and complete alterations to aquatic habitats. In addition, pathogenic microbes may be suspended or sorbed to suspended particles in the wastewater. Coliform like *Escherichia coli* and other microbes can reach water supplies, where they cause major human health problems.

Waste managers must communicate with wastewater experts and decision makers, since they both have mutual objectives and may unwittingly be working at cross-purposes. When water pollutants are released from landfills, sludge drying beds, and other waste management processes, water systems received the brunt of impact.

Organic compounds, nutrients, and other wastewater constituents “demand” oxygen. For example, leachate from waste facilities contains nutrients that, when they reach the water systems, affect the amount of dissolved oxygen (DO). The biota in these systems vary in their optimal ranges of growth and metabolism (e.g., algae add some O₂ via photosynthesis, but use some O₂ for metabolism, whereas the bacteria are net consumers of DO).

Both solids content and BOD are commonly used by environmental engineers to quantify water pollution. The BOD is the amount of

oxygen consumed with time. Most of the BOD is attributable to decomposing organic matter under aerobic conditions. However, since it is an empirical test, some of the demand may be “abiotic,” that is, chemical processes other than microbial. The BOD is measured by incubating a sealed sample of water with the wastewater or other water (e.g., water at points downstream from the outfall). The DO is measured before sealing the container, that is, at time = 0 (t_0). After sealing, the container is held for 5 days (t_5), and the DO measured again.

The loss of oxygen is determined by comparing the O_2 concentration of the sample at (t_0) to the concentration at (t_5). Samples are commonly diluted before incubation to prevent the bacteria from depleting all of the oxygen in the sample before the test is complete [12]. Thus BOD_5 is a simple calculation of measured DO at the beginning time, that is, the initial DO (D_1), measured immediately after it is taken from the source minus the DO of the same water measured exactly 5 days after D_1 , that is, D_5 :

$$BOD = \frac{D_1 - D_5}{P} \quad (13.1)$$

where P = decimal volumetric fraction of water utilized. D units are in $mg\ L^{-1}$. If the dilution water is seeded, the calculation becomes:

$$BOD = \frac{(D_1 - D_5) - (B_1 - B_5)f}{P} \quad (13.2)$$

where B_1 = initial DO of seed control, B_5 = final DO of seed control, and f = the ratio of seed in sample to seed in control = $\frac{\% \text{ seed in } D_1}{\% \text{ seed in } B_1}$. B units are in $mg\ L^{-1}$.

For example, to find the BOD_5 value for a 10 mL water sample added to 300 mL of dilution water with a measured DO of $7\ mg\ L^{-1}$ and a measured DO of $4\ mg\ L^{-1}$ 5 days later:

$$P = \frac{10}{300} = 0.03$$

$$BOD_5 = \frac{7 - 4}{0.03} = 100\ mg\ L^{-1}$$

Thus the microbial population in this water is demanding $100\ mg\ L^{-1}$ dissolved oxygen over the 5-day period. So, if a conventional municipal wastewater treatment system is achieving 95% treatment efficiency, the effluent discharged from this plant would be $5\ mg\ L^{-1}$.

Chemical oxygen demand (COD) does not differentiate between biologically available and inert organic matter, and it is a measure of the total quantity of oxygen required to oxidize all organic material completely to carbon dioxide and water. COD values always exceed BOD values for the same sample. COD ($mg\ L^{-1}$) is measured by oxidation using potassium dichromate ($K_2Cr_2O_7$) in the presence of sulfuric acid (H_2SO_4) and silver. By convention, 1 g of carbohydrate or 1 g of protein accounts for about 1 g of COD. On average, the ratio BOD:COD is 0.5. If the ratio is <0.3 , the water sample likely contains elevated concentrations of *recalcitrant* organic compounds, that is, compounds that resist biodegradation [13]. That is, there are numerous carbon-based compounds in the sample, but the microbial populations are not efficiently using them for carbon and energy sources. This is the advantage of having both BOD and COD measurements. Sometimes, however, COD measurements are conducted simply because they require only a few hours compared to the 5 days for BOD.

Since available carbon is a limiting factor in the demand, the BOD reaches a threshold, known as the ultimate carbonaceous BOD. If carbonaceous compounds comprised the entire O_2 demand, the curve would become a plateau (see Fig. 13.2). However, there are other sources of demand. Notably, microbial populations will continue to demand O_2 from the water to degrade other compounds, especially nitrogenous compounds, which account for the bump in the BOD curve [14]. Thus in addition to serving as an indication of the amount of molecular oxygen needed for biological treatment of the organic matter, BOD also provides a guide to sizing a treatment process, assign its efficiency,

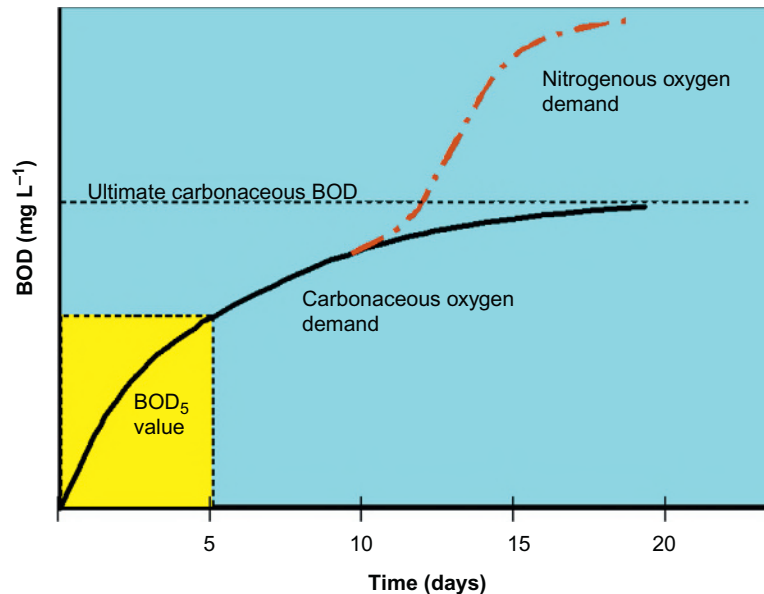


FIG. 13.2 Biochemical oxygen demand (BOD) curve showing ultimate carbonaceous BOD and nitrogenous BOD. Adapted from C. P. Gerba and I. L. Pepper, "Wastewater treatment and biosolids reuse," in: *Environmental Microbiology*, second ed. Elsevier Inc., New York, 2009, pp. 503–530.

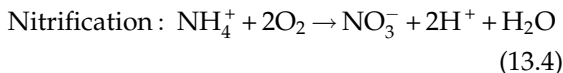
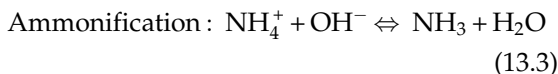
and giving operators and regulators information about whether the facility is meeting its design criteria and is complying with pollution control permits.

If effluent with high BOD concentrations reaches surface waters, it may diminish DO to levels lethal to some fish and many aquatic insects. As the water body reaerates as a result of mixing with the atmosphere and by algal photosynthesis, O_2 is added to the water, the oxygen levels will slowly increase downstream. The drop and rise in DO concentrations downstream from a source of BOD is known as the DO sag curve, because the concentration of dissolved oxygen "sags" as the microbes deplete it. So, the falling O_2 concentrations fall with both time and distance from the point where the high BOD substances enter the water.

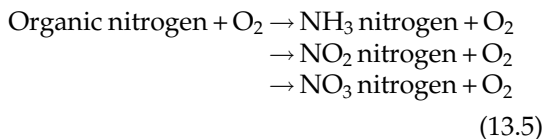
As discussed in [Chapter 33](#), the amount of any substance, for example, nutrient, pollutant, or microbes, that is discharged into a system by point and nonpoint sources is known as the *load*.

[Chapter 33](#) explains how nutrient loading, pollutant loading, and microorganism loading can be quantified as to the gross mass of the substance entering an ecosystem and by the response of the ecosystem to the load. Calculating these loads must account for background sources (sometimes referred to as "natural" sources).

The linkages between biota and their environments are influenced by the availability and forms of nutrients. When rain containing nitrates falls on wetland water and land surfaces, for instance, plant roots take it up and metabolize it into organic forms of nitrogen. Meanwhile, bacteria in sediments reduce it to ammonia. In the opposite direction, the reduced forms are oxidized by other bacteria (e.g., *Nitrosomonas* converts ammonium ions $[NH_4^+]$ to nitrite $[NO_2^-]$, *Nitrobacter* converts the NO_2^- to nitrate $[NO_3^-]$). Thus two opposite reactions are at play constantly in loading scenarios. In this instance, the *ammonification* (or *deamination*) and *nitrification* reactions are as follows:



Note that ammonification is written as an equilibrium reaction, and nitrification is an oxidation reaction. However, the loading depends on numerous environmental conditions, including pH. Thus under acidic conditions, most of the ammonia nitrogen will ionize to the ammonium ion and under basic conditions the nonionized ammonia concentrations will increase in proportion to the ammonium ion concentration. This is important since nonionized ammonia is very toxic to aquatic biota, whereas ionized species are nutrients needed for plants and algae growth. Add to this, the decomposition of organic matter, and the loading becomes a complicated mix of reactions:



Even this is a gross oversimplification, since the oxidation and reduction depend on the types of bacteria present and other physicochemical properties of the water. For example, the O_2 required for nitrification is theoretically $4.56 \text{ mg O}_2 \text{ mg}^{-2} \text{ NH}_4^+$, but this is an *autotrophic* reaction. Thus O_2 is being produced by the nitrifying bacteria, decreasing the amount needed. However, the growth rate of nitrifying microbes is far less than that of *heterotrophic* microbes decomposing organic wastes. Therefore when large amounts of organic matter are being degraded, the nitrifiers' growth rate will be sharply limited by the heterotrophs, which means the rate of nitrification will commensurately be decreased [15]. Furthermore, these same responses to conditions exist for all other nutrients in the system, for example, organic P will be oxidized and oxidized P species reduced, etc. Thus the kinetics of nutrient loading are complex.

3.3 Free Energy and Wastewater Treatment

Both primary and secondary treatments decrease the organic load of the wastewater, that is, the BOD. However, it is the microbial degradation in secondary treatment that accounts for most of the BOD removal. This is accomplished by free energy, that is, the measure of a system's ability to do work (this section is based on the free energy discussion in reference [14]). If reactants have greater free energy than the products in a chemical reaction, then energy is released from the reaction; that is, reaction is exergonic. Conversely, if the products from the reaction have more energy than the reactants, energy is consumed; that is, it is an endergonic reaction. Equilibrium constants are ascertained thermodynamically by employing the Gibbs free energy (G) change for the complete reaction expressed as:

$$\Delta G = \Delta H - T\Delta S \quad (13.6)$$

where ΔG is the energy liberated or absorbed in the equilibrium by the reaction at constant T . ΔH is the system's enthalpy change and ΔS is its entropy change. Enthalpy is the thermodynamic property expressed as:

$$H = U + pV \quad (13.7)$$

where U is the system's internal energy.

The relationship between a change in free energy and equilibria can be expressed by:

$$\Delta G^* = \Delta G_f^{*0} + RT \ln K_{eq} \quad (13.8)$$

where ΔG_f^{*0} = free energy of formation at steady state (kJ g mol^{-1}).

Thus the total energy in systems is known as enthalpy (H) and the usable energy is known as free energy (G). Living cells need G for all chemical reactions, especially cell growth, cell division, and cell metabolism and health. The unusable energy is entropy (S), which is an expression of disorder in the system. Since disorder tends to increase because of the many conversion steps outside and inside of the cell, the

cells have adapted ways of improving efficiencies. This is the key to finding biological treatment technologies. Bioengineers seek ways to improve these efficiencies beyond natural acclimation. Thus to understand both wastewater biotechnologies, the processes that underlie microbial metabolism must be characterized.

All cells must carry out two very basic tasks to survive and grow. They must undergo biosynthesis, that is, they must synthesize new biomolecules to construct cellular components. They must also harvest energy. Metabolism consists

of the aggregate complement of the chemical reactions of these two processes. Thus metabolism is the cellular process that derives energy from a cell's surroundings and uses this energy to operate and to construct even more cellular material.

Energy that does chemical work is exemplified by cellular processes (see Fig. 13.3). Catabolism consists of reactions that react with molecules in the energy source, that is, incoming food, such as carbohydrates. These reactions generate energy by breaking down these larger

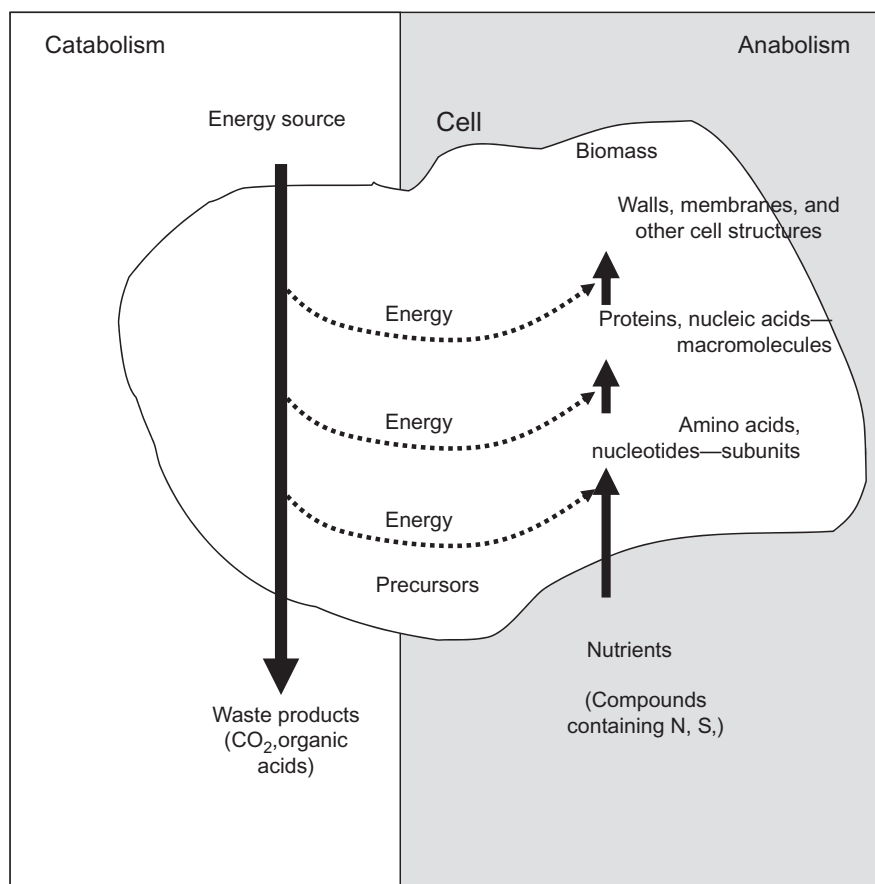


FIG. 13.3 Cellular metabolism results from catabolic reactions that break down compounds to gain energy that is used to build biomolecules (anabolic metabolism) from nutrients that are taken up by the cell, beginning with simple precursors, then subunits, macromolecules. From these biomolecules, the cellular structures are built. From: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*. Elsevier Science, 2015.

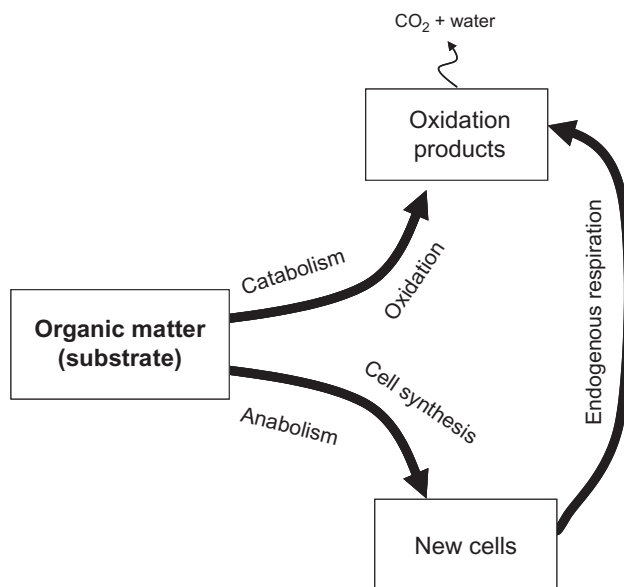
molecules. Anabolism consists of reactions that synthesize parts of the cell, so they require energy; that is, anabolic reactions use the energy gained from the catabolic reactions. Anabolism and catabolism are type of dynamic equilibrium. Anabolism synthesizes while catabolism destroys. However, anabolism can only build the cellular components by using the energy it receives from the catabolistic destruction of organic compounds. Thus as the cell grows, its food supply (organic matter in the wastewater) declines. The efficiency of wastewater treatment depends on the microbial population's ability to use these two metabolic functions to breakdown organic substrates. Thus as shown in Fig. 13.4, the type of wastewater determines the best bacterial species and the conditions needed. Ideally, the microbes in the media in a trickling filter, for example, use the organic compounds as their exclusive source of energy (catabolism) and their sole source of carbon (anabolism).

Microbes, for example, algae, bacteria, and fungi, are essentially miniature and efficient chemical factories that mediate reactions at various rates (kinetics) until equilibrium is reached.

These "simple" organisms (and complex organisms alike) need to transfer energy from one site to another to power their machinery needed to stay alive and reproduce. Microbes play a large role in degrading pollutants, whether in natural attenuation, where the available microbial populations adapt to the hazardous wastes as an energy source, or in engineered systems that do the same in a more highly concentrated substrate. Some of the biotechnological manipulation of microbes is aimed at enhancing their energy use or targeting the catabolic reactions toward specific groups of food, that is, organic compounds.

Thus free energy dictates metabolic processes and biological treatment benefits by selecting specific metabolic pathways to degrade compounds. This occurs in a step-wise progression after the cell contacts the compound. The initial compound, that is, the parent, is converted into intermediate molecules by the chemical reactions and energy exchanges shown in Fig. 13.4. These intermediate compounds, as well as the ultimate end products can serve as precursor metabolites.

FIG. 13.4 Microbial oxidation that occurs during the degradation of organic compounds. Both the catabolic and anabolic processes generate oxidation products.



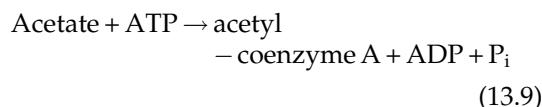
The reactions along the pathway depend on these precursors, electron carriers, the chemical energy, adenosine triphosphate (ATP), and organic catalysts (enzymes). The reactant and product concentrations and environmental conditions, especially pH of the substrate, affect the observed ΔG^* values. If a reaction's ΔG^* is a negative value, the free energy is released and the reaction will occur spontaneously, and the reaction is exergonic. If a reaction's ΔG^* is positive, the reaction will not occur spontaneously. However, the reverse reaction will take place, and the reaction is endergonic.

Time and energy are limiting factors that determine whether a microbe can efficiently mediate a chemical reaction, so catalytic processes are usually needed. Since an *enzyme* is a biological *catalyst*, these compounds (proteins) speed up the chemical reactions of degradation without themselves being used up. They do so by helping to break chemical bonds in the reactant molecules (see Fig. 13.5). By decreasing the activation energy needed, a biochemical reaction can be initiated sooner and easier than if the enzymes were not present. Indeed, enzymes play a very large part in microbial metabolism. They facilitate each step along the metabolic pathway. As catalysts, enzymes reduce the reaction's *activation energy*, which is the minimum free energy required for a molecule to undergo a specific reaction. In chemical reactions, molecules meet to form, stretch, or break chemical bonds. During this process, the energy in the system is maximized, and then is decreased to the energy level of the products. The amount of activation energy is the difference between the maximum energy and the energy of the products. This difference represents the energy barrier that must be overcome for a chemical reaction to take place. Catalysts (in this case, microbial enzymes) speed up and increase the likelihood of a reaction by reducing the amount of energy, that is, the activation energy, needed for the reaction.

Enzymes are usually quite specific. An enzyme is limited in the kinds of substrate that it will

catalyze. Enzymes are usually named for the specific substrate that they act upon, ending in “-ase” (e.g., RNA polymerase is specific to the formation of RNA, but DNA will be blocked). Thus the enzyme is a protein catalyst that has an active site at which the catalysis occurs. The enzyme can bind a limited number of substrate molecules. The binding site is specific, that is, other compounds do not fit the specific three-dimensional shape and structure of the active site (analogous to a specific key fitting a specific lock). The complex that results, that is, the enzyme–substrate complex, yields a product and a free enzyme.

The most common microbial coupling of exergonic and endergonic reactions (see Fig. 13.6) by means of high-energy molecules to yield a net negative free energy is that of the nucleotide, ATP with $\Delta G^* = -50$ to -60 kJ mol^{-1} (-12 to $-15 \text{ kcal mol}^{-1}$). Other high-energy compounds also provide energy for reactions, including guanosine triphosphate, uridine triphosphate, cytosine triphosphate, and phosphoenolpyruvic acid. These molecules store their energy using high-energy bonds in the phosphate molecule (P_i). An example of free energy in microbial degradation is the possible first step in acetate metabolism by bacteria:



In this case, the P_i represents a release of energy available to the cell. Conversely, to add the phosphate to the two- P_i structure of ADP to form the three- P_i ATP requires energy (i.e., it is an *endergonic process*). Thus the microbe stores energy for later use when it adds the P_i to the ATP.

4 METABOLIC MIMICRY

Many wastewater treatment technology classes have been renamed “environmental biotechnology,” since they mimic and enhance natural biological systems to treat wastewater.

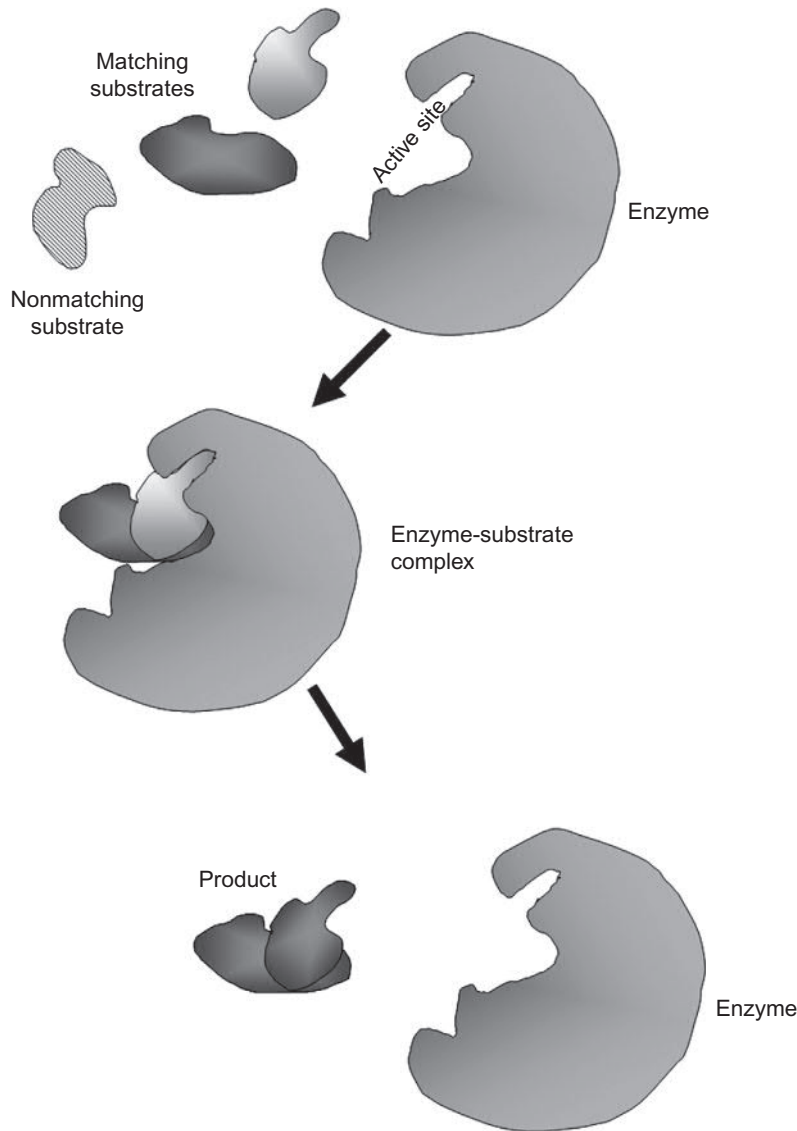


FIG. 13.5 Substrates specific to the enzyme. The breakdown of the enzyme–substrate complex yields a product and the enzyme becomes available for another catalytic reaction. The nonmatching substrate cannot enter into a complex, so it is not affected by the presence of this particular enzyme. However, another enzyme may have the “lock” to match this substrate’s “key.”

Historically, the same species found in soil, manure, and other natural substrates have been acclimated to use certain organic compounds in a waste product as energy sources by three specific mechanisms separately or simultaneously [16, 17]:

- use of the compound as an electron acceptor;
- use of the compound as an electron donor; or
- cometabolism.

Use of a compound as an electron acceptor takes place under reducing conditions. Such

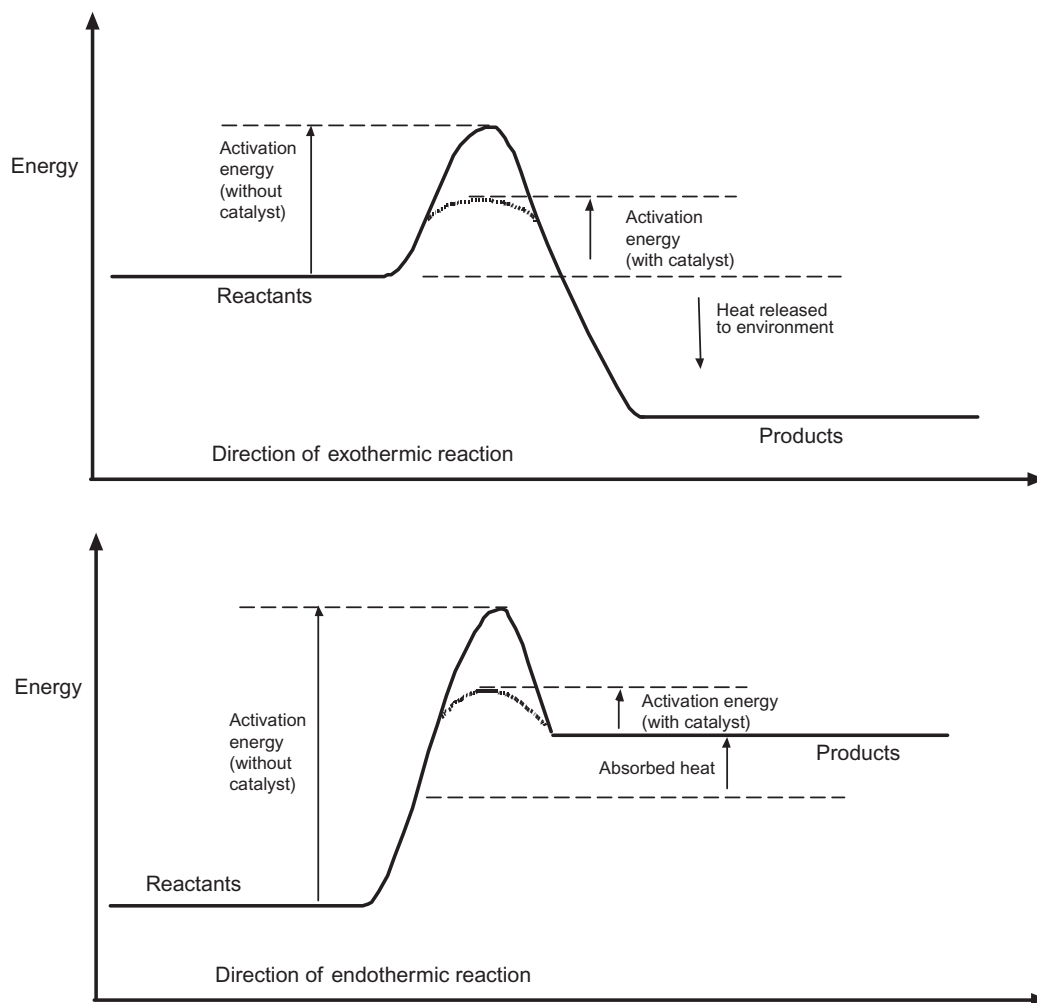


FIG. 13.6 Effect of a catalyst on an exothermic reaction (top) and on an endothermic reaction (bottom).

biotransformation needs a source of carbon (i.e., the electron donor) for microbial growth and metabolism. For example, if the compound contains chlorine, then reductive dehalogenation will occur. That is, the halogens that are bound to carbon and other elements are removed, usually reducing the toxicity of the compound. The electron donor carbon can be gained from various sources, both from natural and anthropogenically derived organic matter.

During electron donation, the compound is used as the primary substrate, so that the microbe obtains its energy and organic carbon from the compound. This may occur either under aerobic and under some anaerobic conditions. Lesser oxidized compounds (e.g., vinyl chloride, dichlorethylene, or 1,2-dichloroethane) are amenable to this mode of biotransformation.

What is actually occurring is known as "cometabolism," that is, the interaction

“between enzyme specificity and metabolic regulation, the metabolic interdependence of microorganisms, and co-substrate requirements in the catabolism of xenobiotic compounds” [18]. Thus the degradation is catalyzed by an enzyme that is fortuitously produced by the organisms for other reasons of survival. The microbe receives no direct benefit from the degradation of the compound and may indeed be harmed or its growth and metabolism be inhibited during cometabolism, but if other energy sources are absent, the microbe is coaxed into using the toxic substance [14]. Of course genetic engineering and synthetic biology have pushed beyond acclimation to generating new strains of microbes tailored to treat specific wastes.

Like wastewater treatment, engineers must find ways to treat solid waste, both abiotically and biotically. For example, a biofilter can treat a specific organic pollutant in solid wastes and wastewater, by combining physical methods, for example, pumping and air sparging, with biotechnological methods. Some processes are exclusively abiotic, for example, thermal treatment, but their residue may call for biotechnological treatment, for example, land application in which the elements in the residue are used as source of nutrients for plants and soil bacteria.

5 WASTEWATER KINETICS

A kinetic reaction is denoted by the one-directional arrow ($\rightarrow$). In the environment, many processes are incomplete, such as the common problem of incomplete combustion in an incinerator and the generation of new compounds other than the two that result from complete oxidation, that is, carbon dioxide and water. The kinetics of a reaction refers to the rate at which reactants are transformed into products. Wastewater kinetics can be described as abiotic or by biological systems, such as microbial metabolism. Since a rate is a change in a

quantity that occurs with time, the wastewater reaction rate at which constituents of wastewater contaminants change into new chemical compounds can be written as:

$$\text{Reaction rate} = \frac{\text{Change in product concentration}}{\text{Corresponding change in time}} \quad (13.10)$$

and

$$\text{Reaction rate} = \frac{\text{Change in reactant concentration}}{\text{Corresponding change in time}} \quad (13.11)$$

When a compound breaks down in nature or in a wastewater treatment system, the change in product concentration drops proportionately with the reactant concentration. Thus for reactant substance *A* the kinetics is:

$$\text{Rate} = -\frac{\Delta(A)}{\Delta t} \quad (13.12)$$

The negative sign denotes that the reactant concentration, that is, the parent contaminant in the wastewater, is decreasing. Thus the degradation product *C* resulting from the concentration increases in proportion to the decreasing concentration of the contaminant *A*:

$$\text{Rate} = \frac{\Delta(C)}{\Delta t} \quad (13.3)$$

By convention, the concentration of the chemical is shown in parentheses to indicate that the system is not at equilibrium. The difference between an initial concentration and a final concentration, $\Delta(X)$:

$$\Delta(X) = \Delta(X)_{\text{final}} - \Delta(X)_{\text{initial}} \quad (13.14)$$

Thus the rate of reaction at any time is the negative of the slope of the tangent to the concentration curve at that specific time (see Fig. 13.7).

For a reaction to occur, the molecules of the reactants must collide. The intensity of these collisions is expressed as the “rate law.” For example, when reacting *A* and *B* to yield product *C*

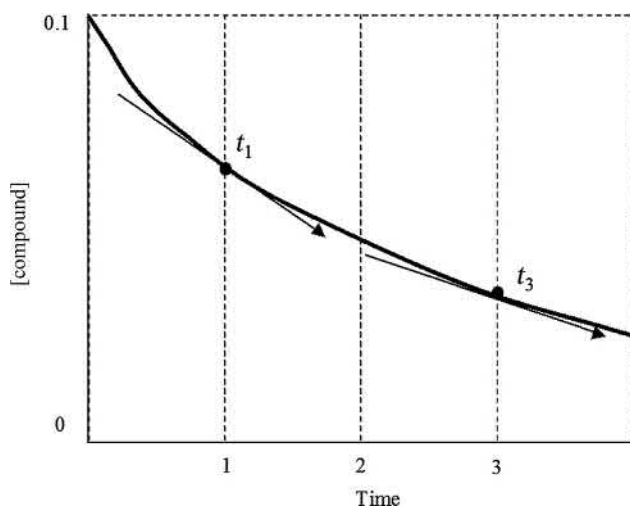


FIG. 13.7 The rate of reaction at any time is the negative of the slope of the tangent to the concentration curve at that time. The rate is higher at t_1 than at t_3 . This kinetic rate is concentration dependent (first order). From: D. A. Vallero, *Fundamentals of Air Pollution*, fifth ed. Waltham, MA: Elsevier Academic Press, 2014, p. 999; J. N. Spencer, G. M. Bodner, and L. H. Rickard, *Chemistry: Structure and Dynamics*. New York: John Wiley & Sons, 2010.

(i.e., $A + B \rightarrow C$), the reaction rate increases in accordance with the increasing concentration of either A or B . If the amount of A is tripled, then the rate of this whole reaction triples. Thus the rate law for such a reaction is:

$$\text{Rate} = k[A][B] \quad (13.15)$$

For the reaction $X + Y \rightarrow Z$, where the rate is only increased if the concentration of X is increased (changing the Y concentration has no effect on the rate law), the rate law must be:

$$\text{Rate} = k[X] \quad (13.16)$$

According to Eqs. 13.10 and 13.11, the concentrations in the rate law are the concentrations of reacting chemical species at any specific point in time during the reaction. The rate expresses how fast reaction is happening at that time. The constant k in the equations is the rate constant, which is unique for every chemical reaction and is a fundamental physical constant for a reaction, depending on the environmental conditions (e.g., pH, temperature, pressure, type of solvent).

The rate constant is the rate of the reaction when all reactants are present in a 1M (M) concentration. Accordingly, the rate constant

k is the rate of reaction under conditions standardized by a unit concentration. By drawing a concentration curve for a contaminant that consists of an infinite number of points at each instant of time, an instantaneous rate can be calculated along the concentration curve. At each point on the curve the rate of reaction is directly proportional to the concentration of the compound at that moment in time. This is a physical demonstration of kinetic order. The overall kinetic order is the sum of the exponents (powers) of all the concentrations in the rate law. So for the rate $k[A][B]$, the overall kinetic order is two. Such a rate describes a second-order reaction because the rate depends on the concentration of the reactant raised to the second power. Other decomposition rates, such as $k[X]$, are first-order reactions because the rate depends on the concentration of the reactant raised to the first power.

The kinetic order of each reactant is the power that its concentration is raised in the rate law. So, $k[A][B]$ is first order for each reactant and $k[X]$ is first-order X and zero-order for Y . In a zero-order reaction, compounds degrade at a constant rate and are independent of reactant concentration.

6 TRANSPORT AND TRANSFORMATION

The waste manager's immediate needs are usually local but may also extend beyond the agency or company. Scale is a key consideration when building a water knowledgebase [19]. To varying extents, water is part of every important physical, chemical, and biological mechanism and process at every scale from planetary to molecular. Water is a transport medium from every scale from intracellular, to the smallest water body, to an ecosystem, to a continent, and to the globe [20]. Fig. 13.1 depicts the "reactors" in the environment [21]. Streams, lakes, aquifers, and other water systems provide the means by which substances enter, change, and exit these reactors. The paths include a range of scales, such as antimicrobial chemicals released into the environment before being taken up by animal and human populations [14]. This involves the cellular scale, in which the chemical then reaches the organism (animal "reactor"), wherein the gut microbes build resistance to even new antimicrobials. The water bodies act at a higher scale (watershed "reactor"), spreading the resistant bacteria and decreasing the effectiveness of antibiotics needed to treat human diseases [21]. In fact, studies have shown that even before a human antibiotic reaches the marketplace, it may have lost substantial effectiveness given that chemically similar veterinary antibiotics may have already passed through Level II in Fig. 13.8, that is, in animals and the pathogenic bacteria have become resistant to the new chemical [21–24].

The waste manager must determine which pollutants will be affected, positively or negatively, by a proposed action, for example, designing and siting a landfill or an incinerator. Choosing the best alternative requires ways to estimate and project what will happen to these pollutants by the available actions and comparing these options by modeling how each contaminant's behavior in the environment. Such

modeling is highly complex and complicated since biological and chemical contaminants can be transported by myriad processes at all scales before reaching human and ecosystem receptors (see Fig. 13.9) [13, 14].

A "parent compound" is transformed into degradation products, sometimes called "chemical daughters" or "progeny." For example, pesticide kinetics often concerns itself with the change of the active ingredient in a pesticide to its degradation products. The degradation products themselves often undergo transformations, depending on environmental conditions. For example, as shown in Fig. 13.9, a parent compound that is highly reactive may degrade within a few minutes after exiting a stack, producing a less reactive degradation product (DP1). Downstream from the effluent discharge, water and compounds within it react with the degradation product, degrading 99% of it within a few hours. These newly transformed compound (DP2) may be less reactive and do not undergo further transformation. At distance A in Fig. 13.10, the measurements would indicate about equal mass of the parent and DP1. However, at distance B, none of the parent compound is detected, and about the same amount of DP1 is measured at distance A because there has been sufficient time since the peak concentration, for this transformation to take place. Very little of the DP2 is present at distance B since it only began to be produced since DP1's degradation. At distance C, sufficient time has lapsed to allow all of mass of DP1 to be degraded into the less reactive DP2. Note that DP2 is not showing signs of decreasing even though all of DP1 is degraded, indicating it is not nearly as reactive as DP1. Indeed, it may travel a long distance before deposition. Persistent compounds can travel many miles before being degraded, volatilized, or deposited [20].

Incidentally, a compound, dissolved in water vapor or sorbed to solids, can move advectively with the stream. If this were the case for the three compounds in Fig. 13.10, the stream

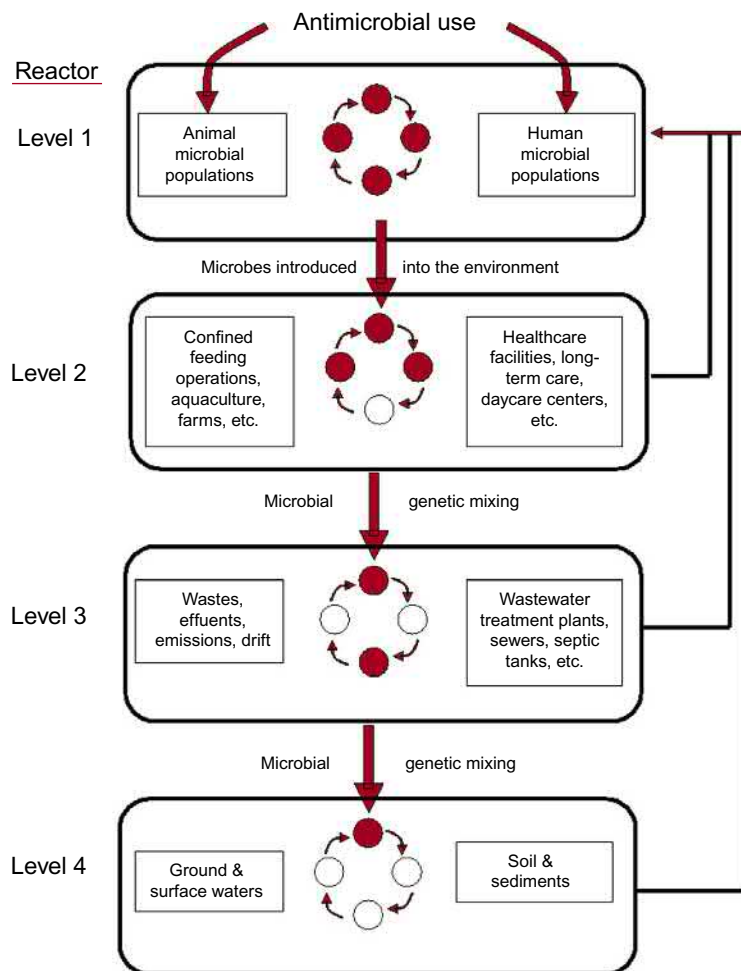


FIG. 13.8 Reactors in the environment. In this case, the change in microbial resistance as a result of genetic mixing at four levels of animal and human reservoirs. Adapted from: F. Baquero, J.-L. Martínez, and R. Cantón, "Antibiotics and antibiotic resistance in water environments," *Curr. Opin. Biotechnol.* 19(3), (2008), pp. 260–265.

concentrations would decrease to nearly zero if all of the solids settle into the sediment. Also, the transformations occur simultaneously in the water, sediment, and organisms. For example, a fraction of DP1 may be broken down abiotically (e.g., hydrolysis) or biotically (microbial metabolism) at distance A, but perhaps between A and B, most of the DP1 will have been absorbed by fish and then stored in their tissue. A portion of DP1 may then convert to DP2 or

even a different degradation product (DP3). The DP1 is no longer available to the water, but continues to degrade and be stored in the fish, after which it may be a food source for other organisms and move through the food chain.

The previous scenario highlights one of the values of taking deposition measurements, that is, to see what was in the atmosphere at the time of the rain event. Another value to see what is reaching the earth's surface, since the air

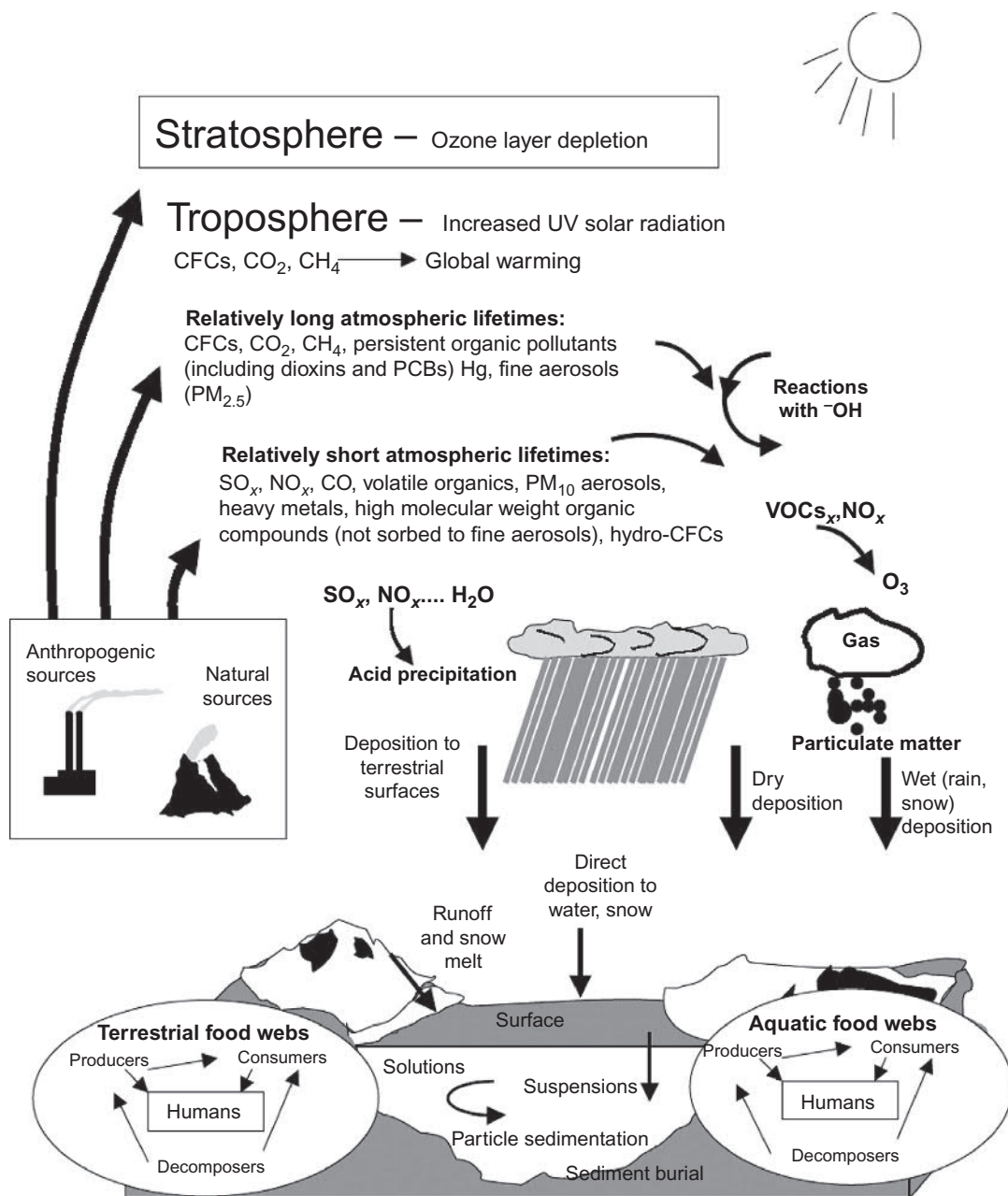


FIG. 13.9 Pollutant transport and transformation processes. From (2003). *The Sound Management of Chemicals (SMOC) Initiative of the Commission for Environmental Cooperation of North America: Overview and Update*. Available from: <http://www3.cec.org/islandora/en/item/2031-overview-and-update-sound-management-chemicals-smoc-initiative-en.pdf>. Adapted in D. Vallero, *Environmental Contaminants: Assessment and Control*. Amsterdam/Boston: Academic Press, 2010.

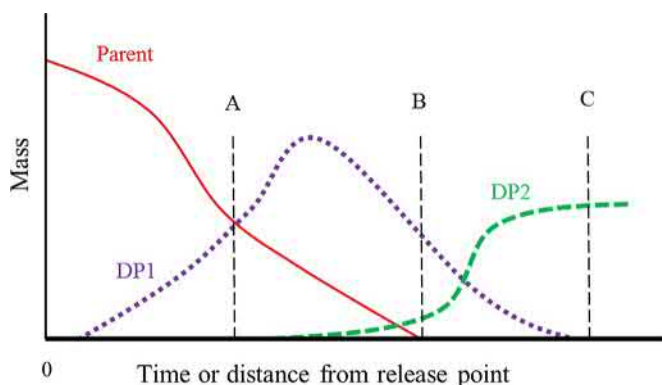


FIG. 13.10 Hypothetical transformation of a reactive compound (parent), followed by the transformation of its first degradation product (DP1) in a plume moving downstream from the point of effluent discharge. DP1 is further degraded into a less reactive chemical species (DP2), indicated by its steady state after all of DP2 has been transformed. DP2 will remain in the water until it is broken down, volatilized, and deposited. Adapted from: D. A. Valero, *Fundamentals of Air Pollution*, fifth ed. Waltham, MA: Elsevier Academic Press, 2014, p. 999.

pollutants can become water or soil pollutants and can harm biota, for example, sulfate compounds that stress vegetation. The combination of deposition and transformation is an example of how physics and chemistry must be considered in concert to determine the severity of air pollution.

In addition, equilibrium reactions also occur in the environment. Of course, getting to equilibrium requires a phase in which the reaction is dominated by kinetics. So, upon reaching equilibrium, the kinetic reactions (one-way arrows) would be replaced by two-way arrows ($\leftrightarrow$). Changes in the environment or in the quantities of reactants and products can invoke a change back to kinetics.

Incomplete reactions are very important sources of environmental contaminants. For example, these reactions generate products of incomplete combustion (PICs), such as CO, PAHs, dioxins, furans, and hexachlorobenzene (HCB). However, even the products of complete combustion are not completely environmentally acceptable. Both carbon dioxide and water are greenhouse gases. They are both essential to life on earth, but excessive amounts of CO₂ are strongly suspected of altering climate, especially increasing the mean surface temperatures on earth. Thus CO₂ is considered by many to be an "air pollutant."

In reality, water pollution results from complex interactions of substances in various states in the many environmental media where

substances are transformed. These transformations may render a compound that was previously not very toxic into a very toxic substance. Conversely, what may have been a precursor to an air pollutant may have been changed into a less toxic compound or compounds. During transport, a pollutant may also undergo chemical changes. These changes may form toxic compounds or other types of problems, for example, they may become stronger greenhouse gases such as CH₄ formed by reduction of CO₂. After deposition, chemical reactions occur in the soil, water, and biota.

Thus pollutants are a result of a mix of chemical reactions each occurring at its own rate. Pollution seldom occurs in a single system. Indeed, a better way to consider these mixed systems is pseudo orders in the rate laws, that is, "pseudo-open" and "pseudo-closed" systems. Applying the qualifier "pseudo" to absolute terms is a good way to describe the actual rates that occur in the environment, as opposed to well-controlled laboratory experiments.

The rate law for a chemical reaction is an equation that links the rate of the reaction with concentrations of reactants and rate constants (commonly, partial order reactions and rate coefficients). The rate is expressed as:

$$r = k[A]^x \times [B]^y \quad (13.17)$$

where k is the rate coefficient, the concentration of each chemical species is in brackets and the

exponents are derived experimentally. A first-order reaction occurs at a linear rate:

$$r = -\frac{d[A]}{dt} = -k[A]^1 = -k[A] \quad (13.18)$$

Similarly, a second-order reaction rate is:

$$r = -\frac{d[B]}{dt} = -k[B]^2 \quad (13.19)$$

or

$$r = -\frac{d[B]}{[B]^2} = -kdt \quad (13.20)$$

The rate equations for third and next orders would follow the same format. In air pollution, numerous reactants are involved in reactions. Thus mixed second-order rate reactions can be expressed as:

$$r = -\frac{d[B]}{dt} = -k[B][A] \quad (13.21)$$

When reaction rates exceed first order, the chemical concentrations can be adjusted so that the kinetics appears to be first order. So, for the simple reaction $2A + B \rightarrow C$, the rate law would be:

$$-\frac{1}{2} \frac{d[A]}{dt} = k[A][B] \quad (13.22)$$

Since the right side is a product of two reactants, the overall rate law is second order, but with excess concentrations of B , then $[B]$ is almost completely unchanged in the reaction, that is $[B]$ changes very much more slowly than does $[A]$. In this instance, Eq. 13.22 can be better written as:

$$-\frac{1}{2} \frac{d[A]}{dt} \approx k'[A][B] \quad (13.23)$$

where k' is a pseudo-first-order rate coefficient (units are inverse time, s^{-1}).

7 ENVIRONMENTAL FATE

After the processes and mechanisms of transport and transformation, the pollutant reaches its fate; this can be expressed in terms of physical

and chemical properties together with the location of the substance, that is, what it becomes and the site where it remains. The "it" may be the released pollutant or it may be a degradation product, that is, a degradate. For example, the municipal wastewater and landfills receive pharmaceuticals and personal care products (PCPs) in their wastestreams [25]. The degradates of these chemicals can be more concentrated than the parent substances that the residents use. For example, the antiinflammatory drug, ibuprofen, and its metabolites, for example, carboxyibuprofen and hydroxyibuprofen have been measured in influent and effluent samples in municipal wastewater. Carboxyibuprofen has been found at higher concentrations than ibuprofen and hydroxyibuprofen in the influent [26]. Some of the transformation takes place within the human who ingests the drug, so what enters the wastewater is about 15% ibuprofen, 43% carboxyibuprofen, and 26% hydroxyibuprofen. The degradation continues in the environment. Hydroxyibuprofen has been found at higher concentrations than the other two chemicals in seawater. Similar results have been shown for other over-the-counter pharmaceuticals and PCPs [27].

Within a geologic timeframe, the environmental fate is not permanent. Indeed, a chemical may have many fates, since a substance undergoes numerous changes in location and form before reaching its final fate. With changes in conditions, this fate will also change. This new fate also becomes a release. A wastewater pollutant's fate may be the sediment at a stream bottom, but with changes in hydrological conditions like a hurricane or a dredging project, the pollutant may be rereleased from the sediment, transported in the river, and find its way to an alluvial aquifer, that is, its new fate is the groundwater. The fate may again change if the aquifer is a source of drinking water, for example, a public water supply, where the water is drawn and treated. The treatment may be complete, so that the pollutant's new fate is

the treatment sludge. If incomplete, the amount of pollutant that remains untreated may be transported in the water supply to consumers. Within the body of the consumer, the pollutant may undergo toxicokinetics, that is, absorption, distribution, metabolism, and excretion. The amount that is absorbed, but not excreted stays within the body, that is, the body burden. Thus the new fate is a person's tissues.

Of course, body burden has a time function. A very persistent compound may remain in tissue for years, whereas a more reactive compound may change very rapidly, for example, a few hours. For example, if a person is exposed to a chemical at $225 \text{ ng } 100 \text{ kg}^{-1} \text{ year}^{-1}$ from drinking, $25 \text{ ng } 100 \text{ kg}^{-1} \text{ year}^{-1}$ from ingesting food, and $50 \text{ ng } 100 \text{ kg}^{-1} \text{ year}^{-1}$ from contact through skin, the person's total accumulation of for the 20-year period would be $(225 + 25 + 50) \text{ ng} \times 20 = 7000 \text{ ng}$. This person's body would have built up $7 \mu\text{g}$ of the chemical over this 20-year span. As mentioned, the chemical dose during that period must not only include the absorption rate, but the distribution, metabolism, and elimination rates. If 80% of ingested chemical is absorbed by the gastrointestinal tract [28], with 90% of this amount cleared from the person's body each year, the net amount is the product of the accumulated amount times the absorption rate times the remaining amount after clearance (i.e., $1 - \text{clearance rate}$):

$$7 \mu\text{g} \times 0.8 \times (1 - 0.9) = 0.56 \mu\text{g}$$

Thus the person has $0.56 \mu\text{g}$ per 100 kg , that is, an accumulation concentration of $0.0056 \mu\text{g}$ or 5.6 mg of the chemical body burden after 20 years of exposure. This calculated body burden would increase if the absorption rate increased. The body burden would decrease if the clearance rate increased. For hydrophobic and lipophilic compounds, those with large octanol–water partitioning coefficients (K_{ow}) like DDT ($\log K_{ow} = 6.9$) the fate is likely to be in lipid-rich tissues. Thus the clearance rate could be decreased in proportion to the amount

of a compound that is stored in lipids, that is, lipophilic compounds generally have much longer half-lives than hydrophilic compounds in mammals.

Conversely, the clearance rate of a completely reactive, nonbioaccumulating compound would be 100%, that is, none of the compound is stored. However, this does not necessarily mean that the person has no risk. Firstly, many nonpersistent compounds are highly and acutely toxic, so the long-term exposure to a toxic compound could be causing incremental harm. Secondly, even if the body burden of the parent compound is zero, its metabolites may accumulate.

Metabolism must also be considered in fate calculations. The person exposed to DDT would not only have a body burden of the parent DDT, but also of DDT's metabolites, dichlorodiphenyldichloroethylene (DDE) and dichlorodiphenyldichloroethane (DDD) which, like DDT, also persist and bioaccumulate in the body. It is not unusual for the metabolite body burden to exceed that of the parent compound.

Within or outside of the body, a parent compound can undergo metabolism by various processes such as reduction, hydrolysis, or dehalogenation and depending on each metabolite having its own toxicity (see Fig. 13.11). Once formed, the new compounds will differ in severity and type of toxicity, for example, DDE's mechanisms and/or rate in disrupting the endocrine system differ from DDT (i.e., antiandrogenic). Indeed, the metabolites of a nontoxic compound may become toxic by a process known as bioactivation. For example, most polycyclic aromatic hydrocarbons (PAHs), molecularly flat compounds with repeating benzene structures, are highly hydrophobic and difficult for an organism to eliminate (since most blood and cellular fluids are mainly water). One of the most toxic PAHs is benzo(a)pyrene, which is found in cigarette smoke, combustion of coal, coke oven emissions, and numerous other processes that use combustion. In the body, benzo(a)pyrene can react to produce an epoxide

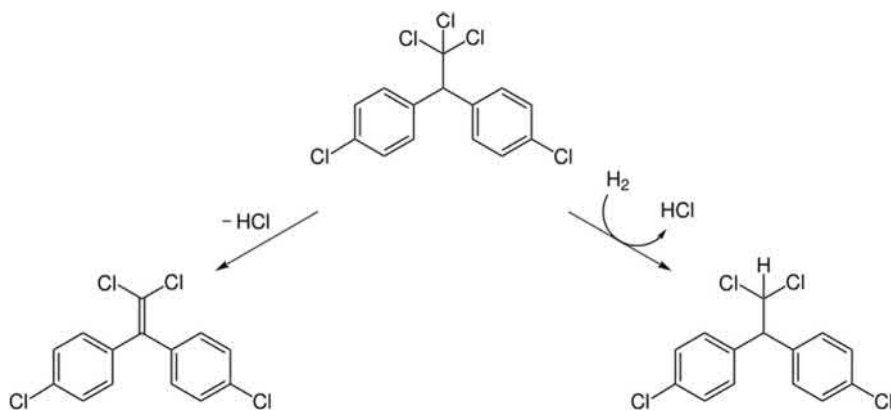


FIG. 13.11 Two degradation pathways for dichlorodiphenyltrichloroethane (DDT): top. *Right*: Reductive dechlorination to form dichlorodiphenyldichloroethane (DDD). *Left*: Elimination of HCl (H_2 addition) to form dichlorodiphenyldichloroethylene (DDE). From: D. A. Vallero, *Fundamentals of Air Pollution*, fifth ed. Waltham, MA: Elsevier Academic Press, 2014, p. 999.

compound that is even more toxic and carcinogenic than the original benzo(a)pyrene (see Fig. 13.12).

The fate can be gradual or may change suddenly in the case of natural disasters and human failure. Wastewater releases, under disaster

situations, can overcome an otherwise well-designed system. Thus the waste manager and engineer must ensure that the uncertainties and complexities posed by a natural disaster can be contained by designing, siting, constructing, and operating their systems to be sufficiently

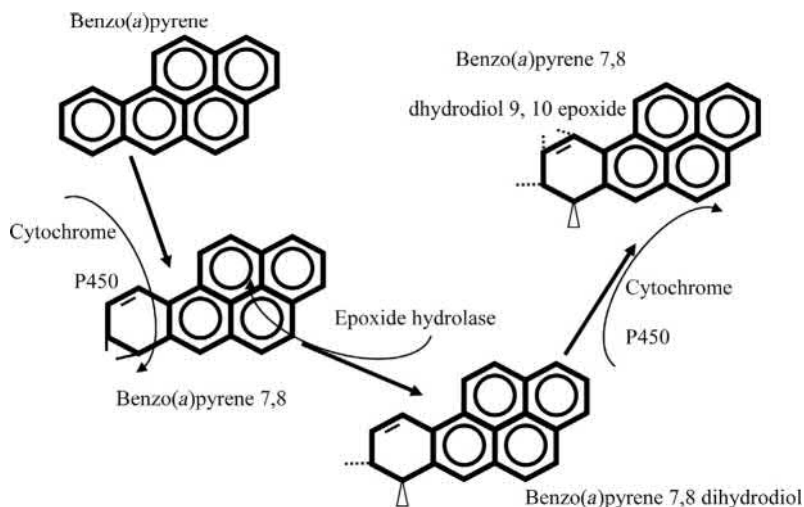


FIG. 13.12 Bioactivation of benzo(a)pyrene to form the carcinogenic metabolite benzo(a)pyrene-7,8-dihydrodiol-9,10-epoxide. During metabolism, the biological catalysts (enzymes) cytochrome P-450 and epoxide hydrolase render greater polarity to the molecule, and in the process form diols and epoxides. These metabolites are more toxic than the parent compound.

resilient. To prepare for human failure, the engineered systems must provide for a sufficient and optimal operational timeframe, in which the failure rate is minimized, that is, the waste management system is reliable [29]. Reliability is discussed in greater detail in [Chapter 36](#).

8 WASTEWATER MECHANISMS

As mentioned, treating wastewater requires a knowledge of physical, chemical, and biological processes. Indeed, wastewater treatment often emulates natural processes, such as decay by microbes in water and soil. Certainly, dissolution of a chemical in water is a dominant process, but as mentioned, many of the compounds of concern are hydrophobic under laboratory conditions, but are often found in wastewater. Thus cosolvation and sorption become the crucial mechanisms at work in wastewater and sludge. Indeed, sorption is arguably the most important transfer process that determines the concentrations of many compounds in surface waters. The physico-chemical transfer [30] of chemical is an interaction of the solute (i.e., the chemical being sorbed) with the surface of a solid surface and can be complex depending on the properties of the chemical and the water. Other fluids are often of such small concentrations that they do not determine the ultimate solid–liquid partitioning. While it is often acceptable to consider “net” sorption, let us consider briefly the four basic types or mechanisms of sorption:

- (a) Adsorption is the process wherein the chemical in solution attaches to a solid surface, which is a common sorption process in clay and organic constituents in soils. This simple adsorption mechanism can occur on clay particles where little carbon is available, such as in groundwater.
- (b) Absorption is the process that often occurs in porous materials so that the solute can diffuse into the particle and be sorbed onto

the inside surfaces of the particle. This commonly results from short-range electrostatic interactions between the surface and the contaminant.

- (c) Chemisorption is the process of integrating a chemical into a porous materials surface via a chemical reaction. In soil, this is usually the result of a covalent reaction between a mineral surface and the contaminant.
- (d) Ion exchange is the process by which positively charged ions (cations) are attracted to negatively charged particle surfaces or negatively charged ions (anions) are attracted to positively charged particle surfaces, causing ions on the particle surfaces to be displaced. Particles undergoing ion exchange can include soils, sediment, airborne particulate matter, or even biota, such as pollen particles. Cation exchange has been characterized as being the second most important chemical process on earth, after photosynthesis. This is because the cation exchange capacity (CEC), and to a lesser degree anion exchange capacity (AEC) in tropical soils, is the means by which nutrients are made available to plant roots. Without this process, the atmospheric nutrients and the minerals in the soil would not come together to provide for the abundant plant life on planet earth [31].

Both physics and chemistry are at work in all four types, all of which are important in wastewater treatment, since they function at surfaces and are crucial to biofilm and molecular exchanges; such exchanges occur in trickling filter systems. The first two types of sorption are predominantly controlled by physical factors, and the second two are combinations of chemical reactions and physical processes. Generally, sorption reactions in biochemodynamic systems involve the three processes [32]:

1. The chemical contaminant’s transport in water due to distributions between the aqueous phase and particles.

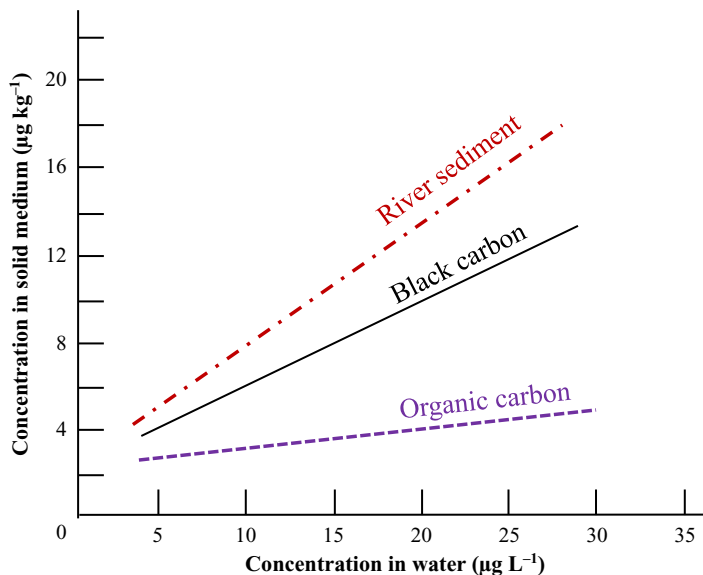
2. The aggregation and transport of the contaminant as a result of electrostatic properties of suspended solids.
3. Surface reactions such as dissociation, surface catalysis, and precipitation of the chemical contaminant.

When a contaminant enters soil, some of the chemical remains in soil solution and the remainder is adsorbed onto the surfaces of the soil particles. Sometimes this sorption is strong due to cations adsorbing to the negatively charged soil particles. In other cases the attraction is weak. Sorption of chemicals on solid surfaces needs to be understood because they hold onto contaminants, not allowing them to move freely with the pore water or in the soil solution. Therefore sorption slows the rate at which substances move downwardly through the soil profile.

Biomolecules and xenobiotic compounds eventually establish a balance between the mass on the solid surfaces and the mass that is in solution. Molecules will migrate from one phase to another to maintain this balance. The properties of both the chemical and the soil (or other matrix) will determine how and at what rates the molecules partition into the solid and liquid phases. These physicochemical relationships, known as sorption isotherms, are found experimentally. Fig. 13.13 illustrates three isotherms for an organic compound, using three different substrates [35].

The x -axis in Fig. 13.13 shows the concentration of pyrene dissolved in water, and the y -axis shows the concentration in the solid phase. Each line represents the relationship between these concentrations for a single soil or sediment. A straight-line segment through the origin

FIG. 13.13 Example sorption isotherms for an organic compound onto three different media. In this case, the compound has a higher affinity, i.e., higher ratio of solid phase concentration to water concentration, for sediment than the other two substrates. Data from X. Xia, Z. Dai, J. Zhang, *Sorption of phthalate acid esters on black carbon from different sources*, *J. Environ. Monit.* 13(10) (2011) 2858–2864.



represents the data well for the range of concentrations shown. Not all portions of an isotherm are linear and this is particularly true at high concentrations of the contaminant. Linear chemical partitioning can be expressed as:

$$S = K_D \cdot C_W \quad (13.24)$$

where S = concentration of contaminant in the solid phase (mass of solute per mass of soil or sediment), C_W = concentration of contaminant in the liquid phase (mass of solute per volume of pore water), and K_D = partition coefficient (volume of pore water per mass of soil or sediment) for this contaminant in this soil or sediment.

For many chemicals and the substrates (e.g., soils), the partition coefficient can be estimated using:

$$K_D = K_{OC} \cdot C_{org} \quad (13.25)$$

where K_{OC} = organic carbon partition coefficient (volume of pore water per mass of organic carbon) and C_{org} = substrate organic matter (mass of organic carbon per mass of substrate, e.g., soil). K_{OC} values are published in handbooks and manuals. However, it is important to note that these, like other partitioning coefficients, are substrate dependent. Thus when comparing

values, the values must be for the same substrate (e.g., carbon source = anthracite) or otherwise normalized.

The relationship between K_D and K_{OC} helps to approximate the “data poor” information from “data rich” information, that is, a chemical’s unknown K_D from the known K_{OC} of the contaminant and the organic carbon content of the soil horizon of interest. The actual derivation of K_D is:

$$K_D = C_S (C_W)^{-1} \quad (13.26)$$

where C_S is the equilibrium concentration of the solute in the solid phase and C_W is the equilibrium concentration of the solute in the water.

Therefore the solid waste manager may find this relationship useful in linking solid matrices with water, given that K_D is a soil parameter. Indeed, K_D is a direct expression of the partitioning between the aqueous and solid (soil or sediment) phases. A strongly sorbed chemical like a dioxin or the banned pesticide DDT in a landfill or waste site, for example, can have a K_D value exceeding 10^6 . Conversely, a highly hydrophilic, miscible substance like ethanol, acetone, or vinyl chloride, will have K_D values <1 . This relationship between the two phases demonstrated by Eq. 13.27 and Fig. 13.14 is the Freundlich Sorption Isotherm:

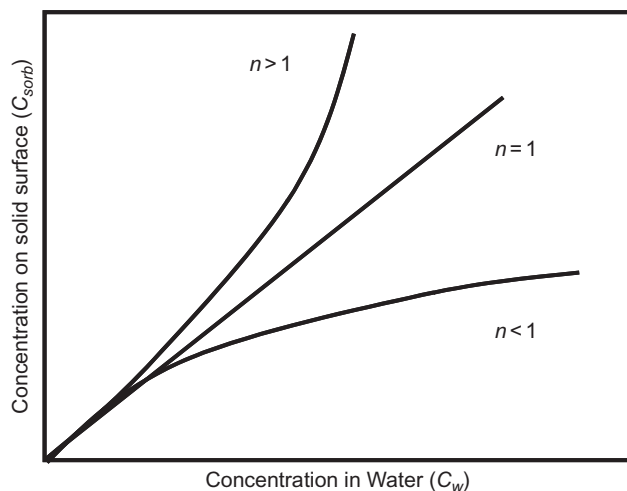


FIG. 13.14 Hypothetical Freundlich isotherms with exponents (n) less than, equal to, and greater than 1, as applied to the equation $C_{\text{soil}} = K_F C_w^n$. Sources: R. Schwarzenbach, P. Gschwend and D. Imboden (1993). *Environmental Organic Chemistry*. John Wiley & Sons, Inc., New York, NY; and H.F. Hemond and E.J. Fechner-Levy (2000). *Chemical Fate and Transport in the Environment*. Academic Press, San Diego, CA.

$$C_{sorb} = K_F \cdot C^n \quad (13.27)$$

where C_{sorb} is the concentration of the sorbed contaminant, that is, the mass sorbed at equilibrium per mass of sorbent; K_F is the Freundlich isotherm constant; and n is the exponent of the chemical concentration curve of the function of C_{sorb} and C_W in Fig. 13.14. The exponent determines the linearity or order of the reaction. Thus if $n=1$, then the isotherm is linear; meaning the more of the contaminant in solution, the more would be expected to be sorbed to surfaces. For values of $n < 1$, the amount of sorption is in smaller proportion to the amount of solution and, conversely, for values of $n > 1$, a greater proportion of sorption occurs with less contaminant in solution. Also note that if $n=1$, then Eq. 13.27 and the Freundlich sorption isotherm are identical [33].

Increasing the organic matter content is elevated in substrates, that is, soil and sediment, is accompanied by an increase in the amount of a contaminant that is sorbed, that is, sorption is directly proportional to the soil/sediment organic matter content. This allows for a conversion of K_D values from those that depend on specific soil or sediment conditions to those that are soil/sediment independent sorption constants, K_{OC} :

$$K_{OC} = K_D \cdot (f_{OC})^{-1} \quad (13.28)$$

where f_{OC} is the dimensionless weight fraction of organic carbon in the soil or sediment. The K_{OC} and K_D have units of mass per volume. Table 13.2 provides the log K_{OC} values that are calculated from chemical structure and those measured empirically for several organic

TABLE 13.2 Calculated and Experimental Organic Carbon Coefficients (K_{OC}) Compared to Octanol–Water Coefficients (K_{ow}) for Selected Contaminants Found at Hazardous Waste Sites

Chemical	log K_{ow}	Calculated		Measured	
		log K_{oc}	K_{oc}	log K_{oc}	K_{oc} (geomean)
Benzene	2.13	1.77	59	1.79	61.7
Bromoform	2.35	1.94	87	2.10	126
Carbon tetrachloride	2.73	2.24	174	2.18	152
Chlorobenzene	2.86	2.34	219	2.35	224
Chloroform	1.92	1.60	40	1.72	52.5
Dichlorobenzene,1,2-(o)	3.43	2.79	617	2.58	379
Dichlorobenzene,1,4-(p)	3.42	2.79	617	2.79	616
1,1-Dichloroethane	1.79	1.50	32	1.73	53.4
1,2-Dichloroethane	1.47	1.24	17	1.58	38.0
1,1-Dichloroethylene	2.13	1.77	59	1.81	65
trans-1,2-Dichloroethylene	2.07	1.72	52	1.58	38
1,2-Dichloropropane	1.97	1.64	44	1.67	47.0
Dieldrin	5.37	4.33	21,380	4.41	25,546
Endosulfan	4.10	3.33	2138	3.31	2040

TABLE 13.2 Calculated and Experimental Organic Carbon Coefficients (K_{OC}) Compared to Octanol–Water Coefficients (K_{ow}) for Selected Contaminants Found at Hazardous Waste Sites—cont'd

Chemical	$\log K_{ow}$	Calculated		Measured	
		$\log K_{oc}$	K_{oc}	$\log K_{oc}$	K_{oc} (geomean)
Endrin	5.06	4.09	12,303	4.03	10,811
Ethyl benzene	3.14	2.56	363	2.31	204
Hexachlorobenzene	5.89	4.74	54,954	4.90	80,000
Methyl bromide	1.19	1.02	10	0.95	9.0
Methyl chloride	0.91	0.80	6	0.78	6.0
Methylene chloride	1.25	1.07	12	1.00	10
Pentachlorobenzene	5.26	4.24	17,378	4.51	32,148
1,1,2,2-Tetrachloroethane	2.39	1.97	93	1.90	79.0
Tetrachloroethylene	2.67	2.19	155	2.42	265
Toluene	2.75	2.26	182	2.15	140
1,2,4-Trichlorobenzene	4.01	3.25	1778	3.22	1659
1,1,1-Trichloroethane	2.48	2.04	110	2.13	135
1,1,2-Trichloroethane	2.05	1.70	50	1.88	75.0
Trichloroethylene	2.71	2.22	166	1.97	94.3
<i>o</i> -Xylene	3.13	2.56	363	2.38	241
<i>m</i> -Xylene	3.20	2.61	407	2.29	196
<i>p</i> -Xylene	3.17	2.59	389	2.49	311

USEPA, (1996). EPA/540/R-96/018, *Soil Screening Guidance: User's Guide*, Washington, D.C.: U.S. Environmental Protection Agency; USEPA, (1996). EPA/540/R-95/128 PB96-963502, *Soil Screening Guidance: Technical Background Document*, Washington, D.C.: U.S. Environmental Protection Agency.

compounds and compares them to the respective K_{ow} values.

8.1 Monod Equation

In previous sections, we have considered metabolism of a single organism. Obviously, treating wastes depends on sufficient bacterial growth to degrade large amounts of organic matter. The Monod equation is an empirically derived expression of the rate of microbial biomass:

$$\mu = \frac{\mu_{max} S}{K_s + S} \quad (13.29)$$

where μ = the specific growth rate of the microbe, μ_{max} = maximum specific growth rate, and K_s = the Monod growth rate coefficient representing the substrate concentration at which the growth rate is half the maximum rate. The μ_{max} is reached at the higher ranges of substrate concentrations. K_s is an expression of the affinity of the microbe for a nutrient, that is, as K_s decreases the more affinity that microbe has for that nutrient (as expressed by the concomitantly increasing μ). Thus wastewater treatment must bring the waste into contact with the microbes and enhance the degradation environment, such as by activated sludge. Engineered

systems may also add activated microbes (if indigenous microbes are not already breaking down the chemical). As these conditions change, the microbes undergo a series of stages [12]:

1. *Lag phase*: Upon initial exposure of the microbes to the chemical contaminant, sufficient time is needed for the organisms to become acclimated.
2. *Accelerated growth rate phase*: Following acclimation, the microbes propagate at an increasing rate. There are two major processes that allow for the degradation of chemical compounds by microbes:
 - (A) The most effective treatment occurs when the organisms use the contaminant exclusively as a food source for their growth, metabolism, and reproduction. As mentioned, this is accomplished by the microbe's ability to produce enzymes that catalyze the chemical contaminant as a carbon source. Recall that the chemical is the microbe's oxygen acceptor during respiration. The microbe produces enzymes that hasten the process of breaking chemical bonds and transferring electrons from the contaminant to an electron acceptor (oxygen for aerobic respiration, and metals (e.g., iron and manganese) and inorganic chemicals (e.g., nitrates and sulfates) for anaerobic respiration).
 - (B) A second, less effective process is known as "secondary utilization." Microbes can transform chemical contaminants although the reaction provides no direct benefit to the microbial cell. Probably the most common, at least best-understood secondary utilization process is *cometabolism*, wherein the microbes break down chemicals coincidentally with enzymes that they normally synthesize for metabolism or detoxification. A case is the methane-oxidizing bacteria that happen to degrade chlorinated

hydrocarbons, benzene, phenol, and toluene by producing enzymes needed to transfer electrons to methane (i.e., the bacterium's normal electron acceptor). The normal methane oxidation enzymes auspiciously degrade the chemical contaminants, even though the chemicals cannot serve as the primary food source for the bacteria.

3. *Exponential phase*: The cell mass and the number of cells are growing exponentially by binary fission.
4. *Declining growth phase*: Cell mass and numbers of cells continue to grow, but at a decreasing rate. This is usually due to depletion of the food and electron source (i.e., the contaminant, hopefully). Other limiting factors could also come into play, such as some of the newly generated chemicals ("degradates") inhibiting the growth of the microbes due to their toxicity.
5. *Stationary phase*: Cell decay is about equal to cell propagation during this time.
6. *Decay*: Cell decay now exceeds cell propagation.
7. *Exponential death phase*: Cells are dying exponentially as cells no longer grow or propagate. Under optimal conditions, this indicates successful bioremediation because the food source (toxic organics) is entirely used up.

The cycle will repeat if the microbes are again introduced to another slug of food (organic compounds).

9 WASTEWATER DATA AND KNOWLEDGEBASES

The waste manager needs reliable knowledgebases. The water knowledgebase must include key aspects of both water resources and water quality data. The U.S. government makes both types available. The U.S. Geological

Survey (USGS) maintains excellent databases to support water resource decisions, including aquifer features like storage capacity and transmissivity. To a lesser extent, the USGS also gathers data on water quality. Conversely, the U.S. EPA has a greater focus on water quality, limiting its interest in water resources to potable water supplies and ground water contamination [34]. Often, this part of the knowledgebase is not owned by most users, but is taken from generally available databases, especially those housed on governmental and institutional portals and websites.

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Recovered Paper

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OUTLINE

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1 INTRODUCTION

Paper is the most commonly recycled material in use today. Over the past several years, over 60% of all paper produced in the United States has been recycled, reaching a high of 67.2% in 2016 [1]. The American Forest and Paper Association (AF&PA) has set a recovery goal of 70% by 2020 [1]. Similar amounts are recovered worldwide. Recovered paper, as a raw material for papermaking, is as important to the paper industry as chemically pulped virgin fiber. Within the paper industry, the term *waste paper* is rarely used, the preferred term

being *recovered paper*, which better reflects its value and importance as a raw material. The terms *recycled paper* and *secondary fiber* are also often used to refer to this waste stream.

Recovered paper, or waste paper, can come from a number of different sources, including internally at the paper mill. A number of different terms are used to indicate when in the life cycle of the paper that it is returned for recycling (Fig. 14.1).

- *Postconsumer recycled fiber*: Paper that is recycled after its final use by the consumer and recovered from homes, offices, and retail locations. This type of waste paper is often the

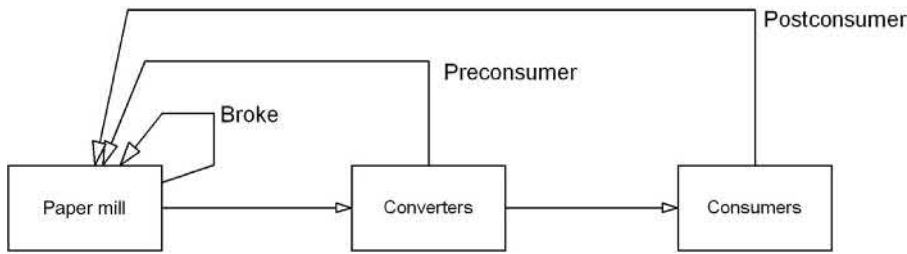


FIG. 14.1 Overview of the life cycle of recovered paper. Paper can be recycled internally within the paper mill (broke), returned to the mill from converting operations (preconsumer), or collected after its final use (postconsumer).

most contaminated and difficult to collect and recycle as it often must be separated from municipal waste [2].

- *Preconsumer recycled fiber*: Paper that is recycled during the manufacturing or conversion process of paper into consumer products such as envelopes. This recycled paper consists primarily of the trimmings and rejected or obsolete products and represents a relatively clean source of fiber for papermaking [2].
- *Broke*: Paper recycled internally within a single mill and is typically trimmings and paper that does not meet the specification of the grade (type of paper) being made. Broke can represent from 5% to 25% of the production of a mill depending on the grade being produced and the efficiency of the machine. The broke may be recycled into the same grade of paper or into a different grade of paper being made at the same mill.

In general, only the first two categories (post-consumer recycled fiber and preconsumer recycled fiber) are considered recovered waste paper; broke is not typically considered recovered waste paper as it had never left the manufacturing site. More information about papermaking can be found in a number of textbooks on the subject [3,4] and general references [5–7].

1.1 History of Use

Papermakers have been reusing their raw materials to create new paper from the earliest

history of papermaking. While the making of paper dates back to ancient China, when the first sheets were made from the bark of the mulberry tree in the first and second century CE, it was not until the invention of the printing press and the industrialization of the papermaking process in the late 18th century CE that demand for paper necessitated a wider range of raw materials to be used for papermaking. Before that time, most paper was made from recycled textiles, primarily cotton, linen, and hemp. The use of wood as a raw material for papermaking was prompted by the shortage of textile-based raw materials in the 18th and 19th centuries, resulting in the development of technology for the mechanical and chemical pulping of wood into a fiber suitable for papermaking.

The modern papermaking age (since the early 19th century CE) and the conversion to wood as the primary raw material for papermaking resulted in increased recycling for papermaking. The use of recovered paper as a raw material has especially grown in the latter half of the 20th century and into the 21st century due to a number of reasons including increased consumer demand, environmental concerns, government regulations, and improving technology for the use of recovered paper as a raw material. The increased use over the past 30 years has also seen a number of challenges in the use of the raw material that needs to be addressed including the degradation of the raw materials and increased and varied contaminants that need to be removed prior to reuse.

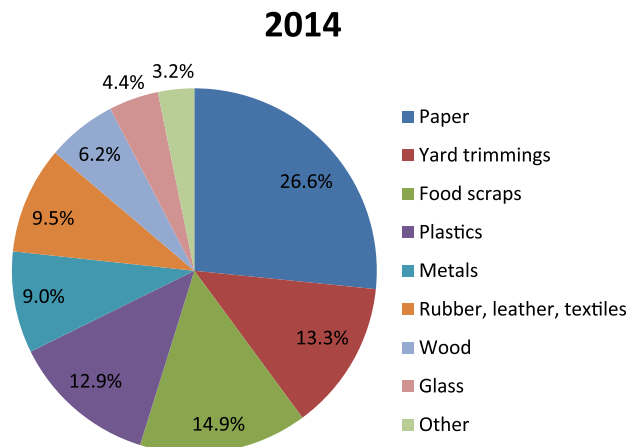


FIG. 14.2 Composition of municipal solid waste in the United States before recycling in 2014 [8].

1.2 Reasons for Use

Paper recycling is important for a number of reasons. Paper is the largest fraction of the municipal solid waste (MSW) stream (Fig. 14.2); recycling can significantly reduce the amount of material heading to the ever-decreasing landfill space. In fact, for every tonne of paper recycled about 2m³ of landfill space are saved. However, it must be noted the percentage of paper in MSW has been steadily decreasing, dropping from 31.0% in 2008 to 26.6% in 2014, as more paper is recovered [8,9]. While it is often stated that recycling saves trees, at least in the United States both wood and recovered paper are in plentiful supply. The decision to use recovered paper is often one of economics and the desired properties of the final paper sheet. In some cases, the use of recycled fiber may be more economical to produce the desired sheet, while in other cases, virgin fiber may be the best. Elsewhere in the world, however, the economics and supply may dictate different choices. Each manufacturer must decide what is best to produce their product under the market conditions at any particular time. Government regulations and recycled content mandates have also been a significant driving force in the increased use of recovered paper in the industry [10,11].

1.3 Industrial Statistics

The amount of paper recovered for reuse has been significantly increasing over the past two decades. In the United States, the percentage of paper recovered for reuse (as a percentage of the amount produced in the United States) has been steadily rising since the mid-1990s (see Fig. 14.3) [12]. While recovery rate has been increasing, the absolute amount recovered has decreased and stabilized due to a reduction in the production of paper in the United States and the reduction and leveling of the amount being landfilled (Fig. 14.4) [13]. In addition, the per capita consumption of paper has decreased over the past several years; for example, in the United States, per capita consumption has decreased from 300.2kg per capita in 2007 to 218.1kg per capita in 2015 [14]. Globally, the per capita consumption has decreased from 59.7kg per capita to 57.0kg per capita over the same time frame [15,16]. Since about 2010, paper production and paper recovery have remained at relatively stable levels due to the changes in the industry and changes in consumer demand for paper. Further increases in the recycling rate will require digging deeper into the available waste streams.

Fig. 14.5 shows the worldwide recovery rate as a fraction of the regions production. As can

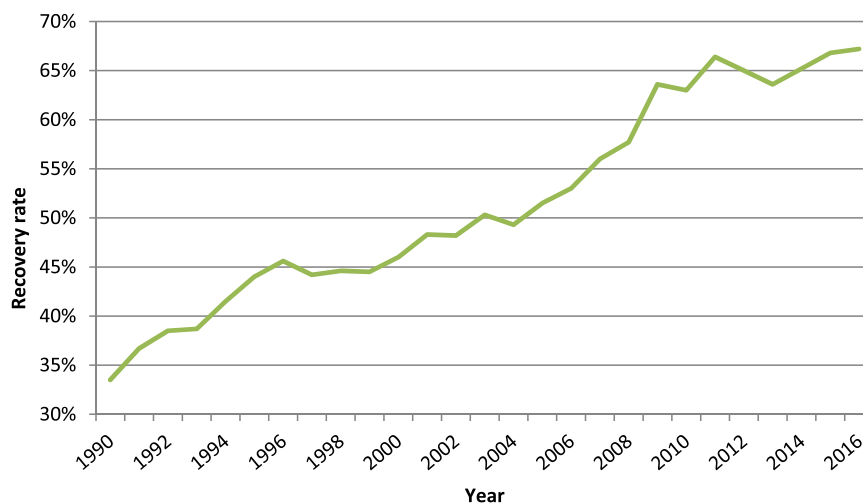


FIG. 14.3 Waste paper recovery rate in the United States from 1993 to 2016 [12].

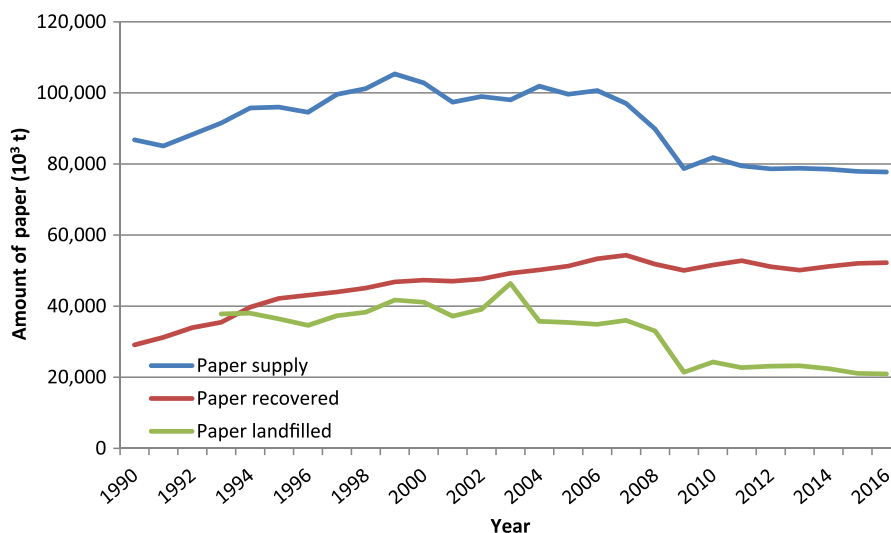


FIG. 14.4 The paper supply compared to the amount of paper recovered and the amount of paper landfilled in the United States [12,13].

be seen, all regions of the world are recovering paper at a rate greater than 50%. In fact, at these recovery rates, recovered paper will soon, if not already, account for more than virgin pulp in terms of fiber content of the worldwide paper and board production [18]. The demand for

recovered paper will continue to be strong, with increasing demand being primarily driven by the fiber needs of China and other countries with limited resources for the production of virgin pulp (Table 14.1). For China, the majority of the recovered paper used is in the form of old

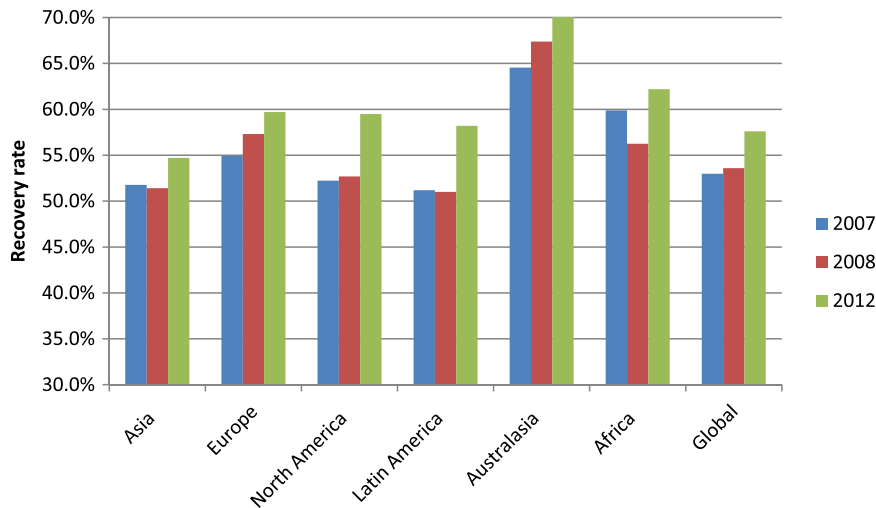


FIG. 14.5 Paper recovery rates (as a fraction of production) regionally around the world [15,17].

TABLE 14.1 Countries Importing the Most Waste Paper in 2008 and 2012 [15,17]

Country	Recovered Paper Imported	
	2008 (10^3 t a^{-1})	2012 (10^3 t a^{-1})
China	24,205	30,070
Indonesia	2080	2290
Canada	1765	690
India	1670	2310
Mexico	1435	1300
South Korea	1307	1470
Thailand	1217	1000
Taiwan	834	830

corrugated containers (OCC), mixed paper, and old newspapers and magazines [17].

2 TYPES OF RECOVERED PAPER

As depicted in Fig. 14.1, recovered paper can come from a number of sources, including the internally recycled broke, preconsumer recycled

paper from converters, and postconsumer recycled paper from various collection methods. Generally, as the paper gets further into the life cycle (from leaving the mill to being used by the consumer), the paper becomes further contaminated, harder to recycle, and worth less in the recovered paper market. To help with the marketing of the recovered paper, a number of organizations have defined various grades of paper and determined their characteristics.

2.1 Recovered Paper Grades

In the United States, recovered paper grades are defined by the Institute of Scrap Recycling Industries, Inc. (ISRI) [19]. These grades determine the characteristics and quality of the recovered paper, allowing comparisons between different suppliers. Table 14.2 provides some examples of the grades defined by ISRI, categorized here into preconsumer paper and postconsumer paper. In this table, prohibitive materials are defined as any material which, by their presence in a packing of paper stock in excess of the amount allowed, will make the packaging unusable as the grade specified or any material that may be damaging to equipment. In addition,

TABLE 14.2 Selected Recovered Paper Grades as Defined by ISRI [19]

Grade	Definition	Prohibitive Materials (%)	Outthrows Allowed (%)
<i>Postconsumer grades</i>			
(1) Residential mixed paper	Consists of a mixture of various qualities of paper not limited as to type of fiber content, normally generated from residential, multimaterial collection programs.	2	5
(6) Old newspaper	Consists of sorted newspapers and other acceptable papers as typically generated by voluntary collection and curbside collection programs.	2	4
(7) News, de-ink quality (#7 ONP)	Consists of sorted, fresh newspapers, not sunburned, and other acceptable papers. This grade may contain magazines.	1	2
(11) Old corrugated containers (OCC)	Consists of corrugated containers having liners of either test liner or kraft.	1	5
(12) Double-sorted old corrugated (DS OCC)	Consists of double-sorted corrugated containers, generated from supermarkets and/or industrial or commercial facilities, having liners of test liner or kraft. Material has been specially sorted to be free of boxboard, off-shore corrugated, plastic, and wax.	0.5	2
(36) Unsorted office paper (UOP)	Consists of printed or unprinted paper typically generated in an office environment that may include a document destruction process. This grade may contain white, colored, coated and uncoated papers, manila and pastel colored file folders.	2	10
(37) Sorted office paper (SOP)	Consists of paper, as typically generated by offices, containing primarily white and colored groundwood-free paper, free of unbleached fiber. May include a small percentage of groundwood computer printout and facsimile paper.	1	5
(40) Sorted white ledger (SWL)	Consists of uncoated, printed or unprinted sheets, shavings, guillotined books, and cuttings of white groundwood-free ledger, bond, writing, and other paper which has similar fiber and filler content.	0.5	2
<i>Preconsumer grades</i>			
(4) Boxboard cuttings	Consists of new cuttings of paperboard used in the manufacture of folding cartons, setup boxes, and similar boxboard products.	0.5	2
(16) Mixed kraft cuttings	Consists of new brown kraft cuttings, sheets, and bag scrap free of stitched paper.	0	0.1
(24) White blank news	Consists of unprinted cuttings and sheets of white newsprint or other uncoated white groundwood paper of similar quality.	0	1
(30) Hard white shavings (HWS)	Consists of shavings or sheets of unprinted, untreated white groundwood-free paper.	0	0.5

sorted recovered paper must be free of food, medical and hazardous wastes, and poisonous or harmful substances. Outthrows are defined as “all papers that are so manufactured or treated or are in such a form as to be unsuitable for consumption as the grade specified” [19]. As can be seen from the table, the postconsumer recovered papers have a much higher tolerance for contaminating materials than the preconsumer grades. The price that each grade demands is strongly dependent on the amount of contamination that is present, which usually must be removed in the recycling process.

In Europe, a similar classification system defining the various types and qualities of recovered paper was created by the European Recovered Paper Association (ERPA) and the Confederation of European Paper Industries (CEPI) [20]. In this system (see Table 14.3), recovered paper is first classified into a number of broad groups, depending on the quality and homogeneity of the paper collected. In general, groups 1 and 2 tend to be the postconsumer grades such as various mixed papers that are collected from residential and commercial collection systems. Groups 3 and 4 tend to be of a higher quality and represent primarily those preconsumer grades collected from paper converters. Group 5 represents a variety of specialty grades that may be of interest only to the producers of specific grades of paper. As in the American classification system, the amount of unwanted materials and nonpaper components is strictly limited depending on the particular types of recovered paper. As can be seen from these definitions, recovered paper is a well-specified commodity that is regularly traded both within various countries and globally.

2.2 Recovered Paper Collection

Recovered paper collection is done in a number of different ways, depending on the type of paper being collected and the source of the paper. In general, preconsumer recycled paper

is easier to collect as it tends to be concentrated in specific manufacturing locations and also tends to be much more homogeneous and less contaminated. These collections, often of the form of cuttings, trimmings, and over issues, are typically baled and packaged directly at the collection site with little additional processing needed [21].

The recovery of postconsumer recycled paper is more difficult as the sources tend to be less concentrated and the paper is often mixed in terms of the types of paper as well as being mixed with other waste. Some postconsumer waste paper grades, such as sorted office paper (see Table 14.2), can be relatively clean as they are collected in dedicated locations, baled, and collected. Often, these collections can be sold to the recycled fiber users directly with little additional processing.

Additional postconsumer recycled paper is collected through municipal collection systems. These papers tend to be the least homogeneous and require the greatest amount of processing and handling to be usable as recovered paper. The collection of these types of paper can be done through a number of different mechanisms including pickup containers, drop-off containers, curbside collection, and other systems. While curbside collection is the most convenient for the consumer, it results in an extremely diffuse source. The effectiveness of curbside recycling in relation to population density can be easily seen with the variation of access across the United States. Heavily populated areas (population greater than 250,000) have much greater access to recycling programs than less populated or unincorporated areas. Overall in the United States in 2015, 73% of the population has access to curbside recycling, 21% has access to drop-off recycling programs, and 94% has access to some type of recycling program [22]. This access has increased over the past 10 years.

These collection methods depend heavily on the final user separating the paper from the MSW stream to be effective. This can be done

TABLE 14.3 Selected Paper Grades as Defined by CEPI and ERPA [20]

Group	Grade	Definition	Maximum Nonpaper Component	Maximum Total Unwanted Materials
<i>Group 1—Ordinary grades</i>				
1.01.00	Ordinary mixed paper and board	A mixture of various grades of paper and board	1.5	3
1.02.00	Mixed papers and boards	A mixture of various qualities of paper and board, containing a maximum of 40 of newspapers and magazines	1.5	2.5
1.05.00	Ordinary corrugated containers	Used boxes and sheets of corrugated board of various qualities, may include 10 of other packaging papers and boards	1.5	2.5
1.09.00	Newspapers and magazines	Mixture of newspapers and magazines (predominantly unsold); each of them with a minimum of 30	0.5	2.5
<i>Group 2—Medium grades</i>				
2.01.00	Newspapers	Newspapers, containing a maximum of five of newspapers or advertisements colored in the mass	0.5	1.5
2.05.00	Ordinary sorted office paper	Paper, as typically generated by offices, shredded or unshredded, printed, may contain colored papers, with a minimum 60 woodfree paper, free of carbon and principally free from carbonless copy paper (ccp)/no carbon required (NCR), less than 10 unbleached fibers including manila envelopes and file covers, less than 5 newspapers and packaging	1.0	2.0
<i>Group 3—High grades</i>				
3.04.00	Tear white shavings	White wood free lightly printed shavings without glue, free from wet-strength paper and paper colored in the mass	0.5	1.0
3.05.00	White wood free letters	Sorted uncoated white wood free printing and writing papers, printed, free from cash books, carbon paper, and nonwater soluble adhesives. May contain five mechanical pulp-based paper	0.5	1.0

TABLE 14.3 Selected Paper Grades as Defined by CEPI and ERPA [20]—cont'd

Group	Grade	Definition	Maximum Nonpaper Component	Maximum Total Unwanted Materials
3.14.00	White newsprint	Shavings and sheets of white unprinted newsprint, free from magazine paper and glue	0.25	0.5
<i>Group 4—Kraft grades</i>				
4.01.00	Unused board and shavings of corrugated materials	Unused boxes, sheets and shavings of corrugated board, with liners of kraft and/or testliner	0.25	0.5
4.02.00	Used corrugated kraft 1	Used boxes of corrugated board, with kraft liners only, the fluting made from chemo thermo mechanical pulp	1.0	2.5
4.07.00	New kraft	Shavings and other new kraft paper and board of a natural shade	0.5	1.0
<i>Group 5—Special grades</i>				
5.01	Mixed papers	A mixture of various paper grades that can be found in the groups 1–5	3.0	3.0
5.02	Mixed packaging	A mixture of various qualities of used paper and board packaging free from graphic papers	1.5	3.0

fairly easily as paper is by far the largest part of the MSW stream before recycling (Fig. 14.2) provided homeowners and businesses separate the recyclable material prior to collection [8]. The recovery of paper after being mixed with other waste is a much more difficult prospect. In this case, the type and amount of contamination can significantly increase the processing costs of using the recovered paper, perhaps beyond economic feasibility. In addition, consideration must also be given to the fate of the balance of the MSW stream. While there is an advantage to remove the paper if the collected MSW is destined for a landfill, separation of paper from MSW that will be incinerated for energy production will reduce the energy value of the material, as paper is a significant portion of the combustible material.

3 PROCESSING OF RECOVERED PAPER

Depending on the source of the recovered paper and the collection method, the recovered paper must be processed before being sent to a mill for recycling. As mentioned before, some grades collected can be sent immediately to the mill for processing, while other grades require more extensive processing before reaching the mill. Even after reaching the mill, the paper often requires extensive processing to remove contaminants and restore the paper-making ability of the fibers. The extent of this processing heavily depends on the grade of paper being recycled and the product that the recovered paper will be used in. While much of the paper recovered in the United States is

converted back into paper products domestically, a good fraction of it is exported to other countries for use and a small fraction of it is used in nonpaper products or uses (see Table 14.4). As can be seen, the most significant change in the use of recovered paper from 2009 to 2016 is the reduction in the use in newsprint (due to the increased use of electronic media) and the increase in the use in containerboard (due to increased online shopping) [24].

3.1 Paper to Paper

In the processing of recovered paper into new paper products, a number of different unit operations are necessary to make the fibers suitable for papermaking. The number and variety of processing steps stem mainly from the large range of contaminants that must be removed from the recovered paper in order to make it usable, as the various operations removing contaminants with differing characteristics. Depending on the cleanliness of the fiber (e.g., whether it is preconsumer or postconsumer and the homogeneity of the recovered paper), more or fewer processing steps would be necessary to recover the paper.

The objective of a recycling mill is to take a material that can vary considerably in properties, and convert it into fiber that can consistently be

made into a final product. Unlike virgin fiber mills producing pulp from wood, the quality of the fiber and the cleanliness of the fiber can vary greatly from day to day or even hour to hour. By comparison, wood as a raw material for producing pulp is much more consistent. Recovered paper can vary greatly in its composition (hardwood content vs. softwood content, mechanical pulp vs. chemical pulp), the types of contaminants present (adhesives, plastics, metals, etc.), and the cleanliness of the stock (inks, dyes, and other foreign materials). While the grading and sorting of this material ameliorates these variations to some degree, recycled mills must still deal with a significant variation in their raw material.

It is impossible to describe a “typical” process used in the recycling of recovered paper, as each grade requires different operations to handle the contaminants that may be present. In fact, the same grade of recovered paper may be treated with significantly different operations depending on the desired final product. Table 14.5 summarizes the primary operations that are used to separate the fiber fraction of the recovered paper from the contaminants.

The various operations separate by a number of different principles and relative characteristics between the fibers and the contaminants.

TABLE 14.4 Uses of Recovered Paper in the United States [23,24]

Recovered Paper	Fraction (%)	
	2009	2016
Net exports	41.3	40.0
Containerboard	29.3	33.7
Boxboard	11.5	11.8
Tissue	8.0	8.4
Newsprint	4.4	0.4
Other	5.4	5.7

TABLE 14.5 Separation Operations Used in the Processing of Recovered Paper to Remove Contaminants From the Feedstock

Unit Operation	Removal Mechanism	Contaminants Removed
Washing	Particle size and shape	Water soluble inks, fine particles
Cleaning	Specific gravity, size, and shape	Dirt, sand, metal, plastics
Screening	Particle size, shape, and deformability	Dirt, metal, large particles
Flotation	Surface characteristics and particle size	Laser and photocopy inks

Washing, which is essentially retaining the fibers on a fine screen while letting the liquid pass through, is primarily used for removing very fine particles and water-soluble inks including those typically used in newspapers. Centrifugal cleaning separates primarily by differences in the specific gravity between the fibers and the contaminants. Cleaners can be used to separate material that is both more dense than fiber (e.g., dirt, metal, etc.) or less dense than fiber (e.g., plastics, most adhesives, etc.) depending on the operation of the cleaners. Screening uses a barrier to prevent the passage of contaminants through the screen while allowing the fibers to pass through. The shape and size of the opening in the screen determines which contaminants are prevented from entering the accepted pulp in the operation. Finally, flotation uses a surfactant to attach the contaminants to air bubbles which are then removed from the surface of the flotation cell as dirty foam. This is the primary mechanism for the removal of laser and photocopy toner from office waste. Greater details of these separation operations can be found in many references and proceedings [6,7,25–27].

Several other unit operations are also used in the recycling of paper into new paper products as listed in Table 14.6. While some of these are basic operations needed to process the paper into pulp suitable for papermaking, some of them are used to address a specific need in the processing of the recovered paper. Repulping is the first necessary step in order to get the fibers into an aqueous slurry for further processing and transport. Fractionation is sometimes used to sort the fibers, typically by length, into those that are more suited for papermaking. Refining is used to improve the surface characteristics of the fibers themselves in order to promote greater fiber-to-fiber bonding. Dispersion is a mechanical action used to further detach any ink particles or other contaminants from the fiber so that it can be removed in one of the separation processes. Since many of the

TABLE 14.6 Other Unit Operations Used in the Processing of Recovered Paper

Unit Operation	Effect on Recovered Paper
Repulping	Breaks down the dry paper into individual fibers by mixing vigorously with water and chemicals if needed.
Fractionation	Separates a fiber mixture into two separate streams typically by fiber length. The long fibers are usually used for papermaking.
Refining	Imparting mechanical action on the fibers to change the surface characteristics to enable the bonding of the fibers to each other.
Dispersion	Detaches ink particles from the fiber and reduces the particle size of contaminants.
Dewatering	Removes excess water from the pulp stock so that it can be further processed.
Bleaching	Enhances the brightness of the resulting pulp using chemical agents such as hydrogen peroxide.

processes must be done at fairly dilute conditions to be effective, it is often necessary to remove or add water from the pulp from one operation to the next. Finally, in cases where the final brightness of the pulp is important, bleaching may be necessary. Again, details of these operations can be found in many references [6, 25–27].

3.2 Paper to Other Products

The various processes used to recycle paper into other products are too numerous to describe in detail in a survey article such as this. However, the varieties of products that can be produced are summarized in Table 14.7. In addition, the processing of recovered paper into usable fiber for papermaking often results in a secondary stream typically termed sludge. While considered a waste product of the recycling process, this stream often can also be used to produce a number of different products [28]. Paper can also be

TABLE 14.7 Nonpaper Products From Recovered Paper and Recovered Paper Sludge

Products From Recovered Paper	Products From Recovered Paper Sludge
Insulation	Fertilizer/soil amender
Animal bedding	Landfill caps
Egg cartons	Construction materials
Planting pots for seedlings	Animal bedding
Lamp shades	Ethanol
Ethanol	Energy
Energy	
Dust masks	

converted to energy through the use of various combustion technologies that are available. Paper, being an organic material, has a relatively high energy value and can make an excellent fuel. In many cases, the paper (or the sludge from the recycling operation) can be co-fired with other fuels in power boilers and can also be processed as fuel for smaller scale (e.g., residential) burners.

4 BARRIERS TO RECOVERED PAPER USE

While there are many benefits to the use of recovered paper, there are a number of issues that will limit its use. Most importantly is the fact that paper is an organic material and subject to wear and degradation each time it is recycled. The drying of paper, one of the last steps in the paper-making process, causes irreversible changes in the structure and morphology of the fibers. The subsequent repulping and processing of the fiber causes damage to the fibers that reduce their strength and bonding ability, causing a degradation of the paper properties made from recycled fiber. This degradation limits the amount of

recycled fiber that can be used, especially in papers that have high strength requirements. Fractionation, the separation of fibers by length and using only the longer and stronger fibers, is one method of ameliorating this degradation. However, a certain fraction of virgin fibers will always be needed to make up the difference [29]. As more paper is recovered to be used in recycled paper, the quality of the paper recovered will continue to degrade.

Most of the easier paper to collect and recycle is already being recovered. For OCC, 92.7% was recovered [30] and newsprint reached 72.2% in 2016. To increase the amount of paper recycling further, collections will need to increase primarily in the postconsumer grades of paper. The incremental paper collected will suffer from greater contamination, less homogeneity, and lower fiber quality. Most of the growth in recovered papers will likely be in the mixed paper categories, which also suffer from greater contamination.

Digging deeper into the recovered paper streams will also have economic and environmental consequences. As the paper recovered becomes more contaminated, greater costs will occur in order to make it suitable for papermaking. The disposal of the separated contaminants will need to be done in an environmentally friendly manner, which will become more costly as landfill space becomes more scarce. Environmental concerns with the use of forests may drive paper producers to use a greater fraction of recycled fiber. In the end, paper producers will usually look to the economic bottom line, using whatever raw material that will produce the needed paper at the lowest cost.

5 CONCLUSIONS

Paper recycling will continue long into the future. It is a key raw material for the papermaking process, representing a significant portion of the fiber used. However, due to the degradation

of the fibers through the papermaking and recycling process, the limit to the amount of paper being recycled is slowly being approached. In addition, there are a number of grades of paper that are currently not recycled and will not be in the foreseeable future. This is particularly true for such personal care products such as toweling and tissue.

Future improvements in recycling will need to deal mainly with the fiber quality issues. If recovered paper is to be used in the higher and more demanding grades of paper, technology will need to be developed to “upgrade” the fibers to meet these needs. While fiber fractionation can improve a portion of the fibers by separating out the longer, stronger fibers, it is at the cost of a portion of the recovered paper.

Technology will also be needed to handle greater levels of contamination in the recovered paper stream. As we delve further into the recycled stream, the contaminant level of the recovered paper will increase. Additionally, as the percentage of recovered paper as a raw material increases, we will see a greater quantity of contaminants carrying over from one cycle to the next.

Research continues at a number of universities, government research centers, and industrial research locations. There are also a number of organizations that deal with the issues of recovered paper. Table 14.8 summarizes a number of these; additional information about recovered paper can be found on their websites.

TABLE 14.8 Organizations Dealing With Waste Paper and Paper Recycling

Organization	Website
Bureau of International Recycling	www.bir.org
Technical Association of the Pulp and Paper Industry	www.tappi.org
American Forest and Paper Association	www.afandpa.org
Institute of Scrap Recycling Industries, Inc.	www.isri.org
European Recovered Paper Association	www.pita.org.uk
Confederation of European Paper Industries	www.cepi.org
European Paper & Packaging Industries	www.paperonline.org
Environmental Protection Agency	www.epa.gov
Confederation of Paper Industries	www.paper.org.uk
Canadian Association of Recycling Industries	www.cari-acir.org
National Recycling Coalition	nrc-recycle.org
Paper and Paperboard Packing Environmental Council	ppec-paper.com
TwoSides	www.twosides.info
Paper and Packaging Board	www.paperandpackaging.org www.howlifeunfolds.com

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Glass Waste

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OUTLINE

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1 THE GLASS INDUSTRY

Glass is in the background of the daily lives of most people. It is manufactured from plentiful raw materials and can be readily reused as feed-stock in glass production. Between 80% and 85% of the mass output from the worldwide glass industry is either in the form of containers for the food, beverage, and pharmaceutical industries, or flat glass for building construction or for motor vehicle manufacture [1]. Other product segments, while only constituting about 15% of the mass output, produce high value technical and consumer products by comparison with container and flat glass. However, the potential for glass recycling comes largely

from the container and flat glass sectors, because of their dominance in terms of mass, and their relatively uniform chemical composition, with soda-lime-silica glass accounting for virtually all the container and flat glass produced. Hence this chapter will focus on these categories of glass when discussing the environmental issues arising from glass production and consumption.

1.1 Glass Production

The demand for glass containers, being mainly dependent on sales of beverages and food, does not fluctuate greatly with business cycles, by contrast with flat glass demand. Annual production has increased over the past decade, but not at

TABLE 15.1 Global Container Glass Production

	Reference Year	Reported Data		Conversion Rate	Production Tonnes 2014 ^{a,b}
		Unit of Measure ^{c,d}	Total		
Europe ^e	2014	Tonnes	22,128,328	1.00	22,130,000
Russian Federation ^f	2014	Tonnes	≈7,000,000	1.00	7,000,000
North America ^g	2014	Tonnes	13,230,000	1.00	13,230,000
South America ^h	2014	US\$ million	1980	1.59	3,154,000
Mexico ^h	2014	US\$ million	1666	1.59	2,650,000
Japan ^h	2014	US\$ million	1671	1.59	2,660,000
China ⁱ	2014	US\$ million	10,872	1.59	17,320,000
India ^h	2014	US\$ million	865	1.59	1,380,000
Sub total					
Rest of world					
Total ^{j,k}	2014	US\$ million	48,300	1.59	77,000,000

^a Europe Market Share—29% of total global tonnage, Research MOZ, 2015, *Global Glass Bottles/Containers Market—By Regions and Vendors*.

^b Mordor Intelligence 2016, *Global Glass Bottles/Containers Market*, Hyderabad APAC region leads the market with a market share of 34% in 2016 while, on the other hand, Europe had a share of 29%.

^c Conversion units to tonnes based on Faraday packaging and glass technology services 2006, *light-weight glass containers—The Route to Effective Waste Minimisation*, WRAP, Banbury, UK.

^d Conversion of US\$ million to tonnages based on ratios in United Nations Statistics Division, 2016, “*Industrial Commodity Statistics Database*” Bottles, Jars and other Containers of Glass.

^e FEVE European Container Glass Federation, 2015, for container glass statistics “*EU Container Glass Production Growth shows Industry Resilience*,” Brussels.

^f Glass International, Redhill, U.K. 2015, “*Russian industry stays positive ahead of Mir Stekla 2015*” http://www.mirstekla-expo.ru/common/img/uploaded/exhibitions/mir_stekla/press_about_us/GlassInternational_March2015.pdf.

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ⁱ Statista, Hamburg, 2017, <https://www.statista.com/forecasts/414675/china-glass-container-manufacture-revenue-forecast-icnea-3055>.

^j Future Market Insights 2016, *Glass Container Market*, London, <https://www.futuremarketinsights.com/reports/container-glass-market>.

^k Research and Markets, 2015, “*Global glass bottles and containers market 2014–20*,” Dublin.

the same rate as growth in demand for packaged beverages and food, because of competition from other packaging materials. Based on the sources cited in Table 15.1, and here [2–4] we have calculated that global production of glass containers in 2014 was 77×10^6 t (77 million tonnes).

Table 15.1 analyses production for 2014 by regional groupings. While the source data and other assumptions for the Europe Union and the USA can be quoted with some confidence, those for other regions are subject to varying degrees of accuracy through incomplete data collection.

Over the decade to 2016, the global glass container market has maintained a compound annual growth rate (CAGR) in the region of 3.5% in terms of value and the number of containers produced [4]. However, due to container light weighting [5–7] CAGR in terms of mass is more in the order of 1%.

By contrast with container glass, the demand for flat glass can be very cyclical, depending on the level of activity in the building construction and automotive industries. Following the financial crisis of 2008 and the knock-on effect in the

construction, motor manufacture, and other industries, there were significant capacity reductions in flat glass manufacturing among many of the traditional producing countries. Thus, the North American float glass industry went from 44 working glass lines in 37 plants to 34 lines in 25 plants between 2005 and 2015. Similarly, several countries in Western Europe also witnessed reductions in capacity from 2005 to 2015. By contrast, the growth in China's flat glass production capacity has more than made up for the reductions in capacity. In 2015 China produced and consumed about 50% of the total flat glass produced globally.

Global flat glass production for 2015 is presented in Table 15.2. As in the case of container glass, we believe that the figures for the European Union and USA are more reliable than some of the data for some of the other regional groupings.

1.2 Environmental Issues

The main environmental impacts in glass making are the high energy use in batch melting, resulting in emissions of combustion gases and the heat reaction of components of the batch mix. The usual way of providing heat to melt

glass is by burning fossil fuels above a bath of batch material, which is continuously fed into, and then withdrawn from the furnace in a molten condition. Heat is provided mainly by radiative transmission from the furnace crown, which is heated by the flames to up to 1650°C, with some coming also from the flames themselves. The molten glass in the furnace is held at a constant temperature for approximately 24h for production of containers and 72h for float glass [8]. In general, the energy necessary for melting and mixing the batch components accounts for over 75% of the total energy requirements of glass manufacture [8] with the raw material procurement and formation of life cycle stages accounting for the other 25%.

While pure silica can be made into high quality glass, this requires the batch to be heated to a temperature of around 2300°C, at which point its viscosity is reduced to a liquid state suitable for the subsequent formulation stage, the 'melting point.' By adding sodium oxide (Na_2O) obtained from the addition of soda ash (Na_2CO_3), the melting point is lowered to about 1500°C [9]. However, the soda makes any glass produced water soluble. To overcome this calcium oxide (CaO), obtained from limestone (CaCO_3) is

TABLE 15.2 Global Flat Glass Production

	≈ Million Tonnes								
	Europe ^a	Russian Federation ^b	North America ^c	South America ^c	Japan ^{d,e}	China ^{f,h}	Sout East Asia	Rest of World ^a	Total ^{d,e}
Flat Glass Capacity (2015)	9.50	1.55	8.60	1.85	1.70	42.50	3.10	20.00	85.00
Flat Glass Production (2015)	8.80	1.13	6.00	1.60	1.50	36.60	2.80	14.78	73.20

^a Glass for Europe, Brussels 2015, "Industry Facts and Figures)," <http://www.glassforeurope.com/en/industry/>.

^b Glass International 2015, Redhill, U.K., "Russian industry stays positive ahead of Mir Stekla 2015."

^c Devklin, K., 2016. National Glass Association and Glass Magazine, "How shifting markets and new players are transforming the float glass industry," <https://glassmagazine.com/article/commercial/world-glass-1614774>.

^d Glass Global Community 2017. Tokyo, "Updated worldwide glass market study 2018."

^e Statista, Hamburg 2018, "Market volume of flat glass worldwide," <https://www.statista.com/statistics/697139/flat-glass-market-volume-worldwide/>.

^f China Statistical Yearbook 2016, "Output of Industrial Products," <http://www.stats.gov.cn/tjsj/ndsj/2016/indexeh.htm>.

^g Cision PR Newswire 2013, "Research Report on China's Glass Industry 2012–17," <https://www.prnewswire.com/news-releases/research-report-on-chinas-glass-industry-2012-2017-211167351.htm>.

^h Converted from weight boxes where 1 weight box = 50 kg of glass.

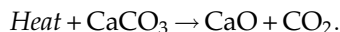
added to the batch to render the glass chemically durable. Magnesium oxide (MgO) and aluminum oxide (Al_2O_3) may also be used to enhance the chemical durability, while other materials are added to provide color. The resulting glass contains about 70%–74% silica, 12%–15% sodium oxide, and 10%–15% calcium oxide by weight, plus a small amount of coloring and other material and is called silica-soda-lime glass. It accounts for about 90% of manufactured glass.

Fuel oil and natural gas are the predominant energy sources for melting, with a small amount of electricity also used. The theoretical energy requirements for soda-silica-lime glass are given in Table 15.3 [9]. The calculation assumes all available heat is fully utilized and has three components:

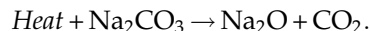
- the heat required to raise the temperature of the raw materials from 20°C to 1500°C
- the latent heat required to enable the reactions between the batch components to form the glass
- the heat content of the gases (principally CO_2) released from the batch during melting

The delivered process energy actually needed is higher than the theoretical figures [9] due to waste gas and structural heat losses, and depends on the furnace efficiency. Large modern cross-fired regenerative furnaces (capacity $>500 \text{ t d}^{-1}$ where d refers to day) operating with a typical energy efficiency of 50% would result in energy use of approximately 5.5 GJ t^{-1} for a container batch containing virgin feedstock only.

The principal emissions to air from the batch melting process result from the combustion of fuel and decomposition of the soda ash and limestone as they heat up. Once limestone is heated to above 850°C, it will start to decompose as in the reaction:



Similarly, soda ash decomposes to produce sodium oxide (Na_2O) as in:



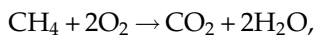
Emissions of gaseous outputs from other additions to the batch produce oxides of sulfur and nitrogen. Based on an input of 150 and 190 kg of limestone and soda ash into the batch mix, 145 kg of process CO_2 per tonne of glass would be produced.

Emissions from combustion per unit of energy will vary depending on the energy source, the most common of which for batch melting is methane processed from natural gas, with fuel oil making up an ever decreasing proportion of the fuel mix based on relative costs. Thus in the USA and European Union it is reported that methane is the predominant fuel, with some electricity in the proportion of 80:20 [10, 11]. NSG Group reported that in 2011 the mix of its fuel use in its glass production operations as methane:oil:electricity = 67:18:15, with oil continuing to make up a decreasing proportion of the total [12].

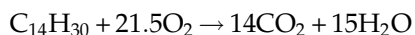
Emissions from methane combustion follow the reaction:

TABLE 15.3 Theoretical Secondary Energy Requirements in Batch Melting Using Virgin Feedstock

	Soda-Lime-Silica Glass GJ t^{-1}
Endothermic melting heat (H_{melt})	1.89
Latent heat of fusion of materials (H_{chem})	0.49
Heat of gases emitted (H_{gas})	0.30
Total energy use	2.68



and that for fuel oil:



Based on a delivered energy use of 5.5GJt^{-1} in the batch melt, and converting this to the mass of methane and fuel oil consumed, CO_2 emissions would be 280 and 415kg t^{-1} of glass, respectively, due to the different combustion carbon outputs for given masses of methane and fuel oil with the same energy content. As all the inputs are in powder or granular form there may also be releases of particulates into the atmosphere. The principal emissions from container glass furnaces to air are summarized in Table 15.4 and include upstream fuel production CO_2 emissions of 50 and 80kg t^{-1} for natural gas and fuel oil, respectively.

There are three broad approaches to reducing the environmental impacts of glass production;

TABLE 15.4 Principal Emissions to Air From Soda-Lime-Silica Glass Batch Melting (kg t^{-1} of Container Glass Produced)

Typical Atmospheric Emissions (kg t of Glass Melted)	
CO_2 using natural gas CH_4	480
CO_2 using fuel oil	640
NO_x	2.4
SO_x	2.5
Dust (without secondary abatement)	0.4
Dust (with secondary abatement)	0.024
HCl (without secondary abatement)	0.041
HCl (with secondary abatement)	0.028
HF (without secondary abatement)	0.008
HF (with secondary abatement)	0.003
H_2O (evaporation and combustion)	1.8

Sources: European Commission 2001, Reference Document on Best Available Techniques in the Glass Manufacturing Industry Tables 3.6–3.17; Department for Business, Energy and Industrial Strategy, 2017 Government GHG Emission Factors for Company Reporting, Table 4.

firstly, reductions in energy use; secondly, “end of pipe” emission abatement measures; and thirdly, for glass containers, product ‘light weighting’ referred to previously [5–7]. Energy intensity efficiencies are achieved through more energy-efficient furnace design and substituting recycled glass cullet for virgin raw materials. Furnaces using natural gas and purified oxygen (gas-oxy furnaces) are largely replacing traditional furnaces heated by using gas and the oxygen present in the air. This results in lower energy consumption and resultant emissions because it is not necessary to heat the atmospheric nitrogen constituting 79% by mass of the air to the temperature of the flames. Less combustion air has to be heated and therefore less energy is lost with the furnace waste gases [13]. It has been estimated that for large efficient regenerative furnaces, energy savings would be between 5% and 20%: see Worrell et al. p. 64 [14].

Further reductions in energy consumption can be obtained through the use of cullet which avoids the use of heat in thermal reactions between batch components and loss of heat in gaseous emissions, and provides additional liquidity at lower temperatures in the batch reducing the energy used to heat the components. Compared to the theoretical energy requirements of 2.7GJt^{-1} for batch melting primary of raw materials, the energy required to simply melt glass is 1.9GJt^{-1} and it is commonly estimated that substituting 10% of cullet for a similar weight of requisite virgin raw material mix can save 2.5% of energy.

Container glass typically has a short life cycle, being primarily used to package beverages and food. Production and use are often within the same country or region, though they may be distant from one another in the case of specialist products, for example, estate bottled wines or pharmaceutical products. By contrast, flat glass, principally used in motor vehicle manufacture and in the construction industry, has a long in-use life span. In the case of buildings, production of the glass used may be distant from its

point of use, though usually within the same national or regional boundaries, while the glass used for motor vehicle windows may well be shipped across national and regional boundaries to its point of use. However, the two types of glass each present their own set of recycling challenges, which will be reviewed separately.

2 GLASS REUSE AND RECYCLING

Within the waste management hierarchy, reuse is considered before moving to the next option down, recycling. In the case of flat glass, because of the dispersed nature of its use, lack of homogeneity, and its long life span, reuse is often not a viable option financially or environmentally. By contrast, the glass used for manufacturing containers has a similar raw material mix, apart from coloring agents, and has a short in-use life. Furthermore, production and use of the containers often take place within the same country or administrative region. For glass containers, the reuse option is therefore considered before that of recycling.

Supermarket retailers are the most influential decision makers in determining the viability of reuse of primary packaging, including glass. Supermarket chains have accelerated the development of distribution systems on the basis of a one-way packaging flow from producer to consumer, and this trend has been further stimulated by the increasing globalization of retail supply chains. Even in supermarket chains in those countries with retake systems, underpinned by container deposit legislation, recycling rather than refill is becoming the norm. In effect, packaging recovery costs have very largely been externalized into the recycling route, where the burden is picked up by consumers, city and regional government recycling infrastructure, and the waste management industry.

For refill systems, the environmental and financial transport burdens of the collect and return system and the cleaning and sterilization

process prior to refill have to be measured against the burdens of cullet collection, processing, and batch melting. This has been the subject of numerous studies demonstrating the significant environmental benefits of reusing rather than recycling glass packaging [15–18].

Even given globalized markets and the current dominance of supermarket and hypermarket chains in retail distribution, there may still be opportunities for smaller scale glass container reuse, for example, in the rapidly growing microbrewery sector serving localized markets in the UK, New England, and Canada. There are also a number of countries and market segments where the refillable glass bottle is used extensively, in many cases supported by container deposit legislation.

The Beer Store of Ontario reports that for the year to April 2011, of the 1.2 billion bottles of beer that organization sold wholesale to retail outlets, 88% of the bottles were refillable, with a return rate of 96% [19]. The PALPA Recycling System in Finland reports that 24% of beverage containers in 2016 were refillable, with a return rate of 97% compared with the return rate of 88% for bottles recycled into cullet [20]. The 2008 Annual Report of Dansk Retursystem A/S showed that, while in Denmark the one-way packaging share of the beverage market is increasing year on year, refillables still accounted for 53% with a 100% return rate [21]. By 2015 this proportion had fallen to 20% [22]. In Germany, reuse of beverage containers has been underpinned by a 72% quota for refillable containers, but here again reuse is under threat from the new packaging regulations in Germany (Verpackungsgesetz) which will become effective from 1 January 2019, whereby the quota is replaced by “promotion” of reusable packaging aiming for a target of 70% [23]. A project led by Glass Technology Services to introduce viable container glass recycling schemes in the Russian Federation indicates that, contrary to previously reported data, nearly all used glass containers are currently disposed of to landfill rather than being refilled or used as cullet [24]. Starting from 1 January 2015 amendments

to Federal Law No. 89-FZ of 24 June 1998 “On Production and Consumption Waste” (“Waste Law”) established extended producers’ responsibility with regard to recycling waste from use of goods, with a 2017 target of 20% for glass containers [25]. In 2015 the State of California achieved a refillable glass bottle recycling rate of 14% compared to 62% for cullet [26]. In other countries the refillable glass container lives on for locally produced beverages or for niche markets, for example, in the UK the refillable milk bottle delivered to and collected from the doorstep. Finally, in some developing nations like India and Brazil, the cost of new bottles often stimulates the informal collection and refill of glass bottles for selling carbonated and other drinks.

2.1 Container Glass Recycling

In theory container glass can be made from 100% cullet, and there is no limitation on the number of times that used container glass can

be fed back into the raw material input cycle. Consequently, the total potential for recycling is all the container glass used in a given period, which, given its short life cycle, is for all practical purposes the amount produced. There are, however, practical limitations to this theoretical 100% use of cullet. Firstly, given the dispersed nature of the waste stream, the marginal environmental and financial burdens of collecting increasing fractions of the postconsumer waste (PCW) container glass waste stream may increase to the point where they exceed the marginal benefits. Secondly, production waste cullet normally contributes about 10% of the batch mix, which limits the amount of PCW cullet that can be used. Having said that, a review of the current status of PCW glass recycling across the world reveals that any theoretical limits on using PCW sourced cullet in container glass production are far from being reached.

Based on public domain information we have estimated worldwide glass container consumption, reuse, and recycling, the results of which

TABLE 15.5 Estimated Global Glass Container Consumption and Recycling Rates

GLASS WASTE MANAGEMENT HIERARCHY	AUSTRALASIA/ OCEANIA			NORTH AMERICA		LATIN AMERICA AND CARIBBEAN		EUROPE				MENA		SUB SAHARAN AFRICA		ASIA				TOTAL
	Australia	New Zealand	Other (excl Hawaii)	U.S.A.	Canada	Brazil	Other	Eu 27 + NOR, CH, Turkey	Russian Federation	Other	Egypt	Other	South Africa	Other	India	China	Japan	Other		
RE-USE					68%	45%		≈ 4%							≤ 70%				36%	
RECYCLE	55%	72%		34%	29%		3% to 10%	74%	20%		≤ 25%		55%			≈ 25%	19%			
SANITARY LANDFILL	45%	28%		66%	3%	55%	90% to 97%	22%							≈ 30%	≈ 75%	81%		64%	
DISPOSAL SITES									80%		≥ 75%		45%							
Year (tonnes million)	2015	2014	2007	2013	2013	2014	NO DATA AVAILABLE	2015	2014	NO DATA AVAILABLE	2007	NO DATA AVAILABLE	2015	NO DATA AVAILABLE	2017	2015	2014	NO DATA AVAILABLE	2014	
Waste Generated	1.10	0.30	0.30	10.00	1.12	1.40		15.94	7.00		≥ 1.9		1.12		2.34	20.00	1.50		77.00	
Recycle/Re-use	0.60	0.22	NO DATA	3.40	1.09	0.63		11.00	1.40		≤ 0.50		0.62		1.64	≈ 5.00	0.36		27.35	

are presented in Table 15.5. Principal data sources are shown in the Annexure to Table 15.5, at the end of this chapter. Where numerical data has not been available, we have made an assessment of the waste disposal options being used in a region or country, based on reviews of the municipal waste management practices obtained from press and industry articles and web sites. These appear as shaded areas in the table. As there is no national or local government infrastructure for municipal waste management and recycling for many developing countries, there is a consequent lack of reliable data in these regions. This does not mean, however, that no recycling or reuse takes place. On the contrary, high rates of urban recycling in many countries are tied in with poverty, so that the very poor, such as the Kabari in India, find a source of income by picking recyclable material from waste left in streets or on municipal dumps [23], though the viability of informal recycling in that country has been negatively impacted by the imposition of a Goods and Services Tax which also applies to recycled products [27, 28].

Calculated consumption amounts to 64×10^6 t for those regions and countries for which data are available and for the years quoted. This compares to the global production of 77×10^6 t presented in Table 15.1. The difference between the two figures is largely due to the lack of consumption data for some regions and the limitation of some data to beverage containers only. In developing countries in particular, there is a huge annual increase in beverage container use, up to 15% p. a. in the case of China [29], but glass takes an increasingly lower share of the total, with predictions for the growth in global container glass consumption in the region of 3%–5%.

2.2 Flat Glass Recycling

The recycling of flat glass largely depends on the way in which construction and demolition wastes (C&DW) and end-of-life vehicles (ELVs) are treated. Approximately 70% of global flat glass production is used in the building and

construction industries, 10% in motor vehicle manufacture [30], and the remainder for other uses. Recycling of such glass is largely dependent on the management of the C&DW and ELV waste streams.

2.2.1 Flat Glass Construction and Demolition Waste

In spite of construction and demolition (C&DW) waste being one of the largest waste flows in the world, there is a significant lack of consistent data about the total waste stream and its management. One estimate for China is that urban C&DW has reached 30%–40% of the total urban waste generation because of the continuing large-scale construction and demolition activities resulting from the accelerated urbanization and city rebuilding. Estimates for China and some other countries/regions are presented in Table 15.6, which also includes the source references. Two studies characterizing the composition C&DW estimated the proportion of flat glass in C&DW to be $0.4 \pm 0.2\%$, and 0.2%, respectively [31, 32]. These ratios are also applied to the estimated C&DW to indicate the size of flat glass waste arising from that source.

Currently there is little recycling of glass by demolition companies due to financial viability. Much brick and concrete C&DW is reused on the construction sites in the form of hard core once it has been crushed to an acceptable particle size. Given that glass is an insignificant part of total C&DW, it is frequently absorbed into the hard core, or any material removed from site for further processing. The exception to this occurs in buildings where glass is a significant part of the external or internal construction. The reader is referred to Chapter 19 for a fuller description of C&DW processing.

If flat glass can be collected without contamination it can be recycled to be incorporated new flat glass production. St. Gobain Glass UK claims that it uses 30% flat glass cullet in the manufacture of its float glass, amounting to

TABLE 15.6 Flat Glass C&D Waste in Selected Countries

Tonnes Million	Europe ^{a,b}	USA ^c	China ^{d-f}	Japan ^g	Brazil ^h	India ⁱ
Year	2010	2014	2014	2011	2016	2015
C&DW	850	534	2500	75.4	70	≤12
Glass proportion ^{a,j}	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%
Glass mass	4.3	2.7	12.5	0.4	0.4	0.1

Principal Data Sources:

^a European Environment Agency, "Europe's Waste Streams" 2015, <https://www.eea.europa.eu/media/infographics/europe2019s-waste-streams-1/view>.

^b Guy Van Marcke de Lummen and Niels Schreuder 'Recycling of Glass from Construction and Demolition Waste', AGC Glass Europe 2013 <http://agc-flattoflat.eu/wp-content/uploads/2017/01/Recycling-of-Glass-from.pdf>.

^c Statista, "Volume of waste generated during construction and demolition in the United States in 2014," <https://www.statista.com/statistics/504120/construction-and-demolition-waste-generation-in-the-us-by-material/>.

^d Beijia Huang, Xiangyu Wang, Harnwei Kua, Yong Geng, Raimund Bleischwitz, Jingzheng Reng, Construction and demolition waste management in China through the 3R principle Resources, Conservation and Recycling Volume 129, February 2018, Pages 36–44, Elsevier.

^e Weisheng Lu, "Estimating the amount of building-related construction and demolition waste in China," Proceedings of the 18th International Symposium on Advancement of Construction Management and Real Estate Springer Verlag, Berlin, 2014.

^f Huabo Duan, Jinhui Li Construction and demolition waste management: China's lessons Waste Management and Research, 2016.

^g Japanese Ministry of the Environment, 2011, in Hideko Yonetani Construction and Demolition Waste Management in Japan, Japan Federation of Construction Contractors.

^h M. Contreras, S.R. Teixeira, M.C. Lucas, L.C.N. Lima, D.S.L. Cardoso, G.A.C. da Silva, G.C. Gregório, A.E. de Souza, A. dos Santos, Recycling of construction and demolition waste for producing new construction material (Brazil case-study), Construction and Building Materials, Volume 123, 1 October 2016, Pages 594–600.

ⁱ Markandeya Raju Ponnada and Kameswari P, "Construction and Demolition Waste Management—A Review," International Journal of Advanced Science and Technology, Vol. 84 (2015), pp. 19–46.

^j Glass for Europe, "EU waste legislation and building glass recycling," Brussels 2014 http://www.glassforeurope.com/images/cont/187_55590_file.pdf.

36,000t per annum [32] which would include production waste. Nevertheless, the incorporation of flat glass C&DW into building aggregates for substrate is likely to remain the main recycling option.

2.2.2 Flat Glass End-of-Life Motor Vehicle (ELV) Waste

Within the European Union the management of ELV waste is regulated by Directive 2000/53/EC, which aims, inter alia, "to increase the re-use, recycling and recovery of materials from ELVs." Total ELV waste for 2007 was calculated as 6,119,842t with 5,024,414t being reused or recycled [33]. According to a report submitted by GHK to the European Union DG XI [34] the average weight of glass per ELV was calculated as 21.2kg, which applied to the 2007 ELV waste

data would give a figure of 130,000t of ELV glass waste in that year.

In the United States the objectives of the Automotive Recyclers Association's include "to promote automotive recycling." A report published in the United States [35] calculated that the number of vehicles taken out of use in the period 1989–98 was 11,374,000 (Table 1–2 of the report, reference [35]) with an average glass weight of 39 kg (86lbs) out of a total average vehicle weight of 1.44t (3165lbs). This would amount to 445,000t of glass waste per annum.

In Japan, roughly 5 million cars are disposed every year, with around a million of these exported as secondhand vehicles. Of the 4 million remaining it is claimed that nearly 100% are subject to recycling, with recycling rate of 75% by vehicle weight [36, 37]. Based on the

EU average of 21.2 kg of glass per vehicle, flat glass waste from ELVs would amount to approximately 85,000 t per annum.

By the end of 2007, there were 43 million vehicles with an average life of 15 years on the roads of China. It is estimated that each year up to 2010 4.8 million vehicles will be scrapped [38]. Using an average of 21.2 kg of glass per vehicle, ELV flat glass waste would amount to around 100,000 t per annum.

There is little, if any, collection of ELV glass for feeding back into the flat glass production loop, and the glass is generally treated as a waste product from the metal and other materials recovered from ELVs (see Chapter 10 of this handbook for a description of ELV recycling).

2.3 Summary of Glass Waste Streams

Based on data presented in the preceding sections, the relative importance of the three principal glass waste streams in terms of mass is summarized in the following table. Despite the variation in the source years and assumptions for the data presented, the many orders of magnitude difference between the three waste streams illustrates the dominant position that recycling container glass, compared to flat glass, can play in the recycling challenge to reduce the environmental and resource impacts of glass production (Table 15.7).

3 CONTAINER GLASS RECYCLING PROCESSES

While waste recycling has become regarded as the waste management option of choice, it has to be recognized that it carries its own environmental and financial burdens [39]. Conceptually, converting postconsumer glass into cullet is a straightforward process of collecting material and removing contaminants, followed by color separation and crushing to feedstock size ready for inclusion in the batch melt, but in practice this is often difficult to achieve. Furthermore, in the drive to achieve high levels of recycling, sight is often lost of the aim of optimizing the environmental gains, or at least this becomes of secondary importance.

In Table 15.8 some key characteristics of container glass recycling have been classified according to the end use of the cullet. Using cullet to produce containers is the most environmentally benign option, not only because of the energy saved in the batch melt, but also because the used glass containers can be fed back into the product loop continuously. The ability to do so depends on their being sufficient demand, which in turn requires that the cullet supplied meets the manufacturer's specification for color mix and purity, for example, in the U.K. the WRAP PAS 101 specification and in the United

TABLE 15.7 Relative Mass of Four Glass Waste Streams

			EU 28	USA	Japan	China
Container Glass		Year	2015	2013	2014	2015
		Tonnes million	15.94	10.00	1.50	20.00
Flat Glass	C&DW	Year	2010	2014	2011	2014
		Tonnes million	2.6	1.6	0.2	7.5
	ELVs	Year	2016	2015	Pre 2005	2007
		Tonnes million	0.15	0.25	0.08	0.10
Proportion flat glass of total			15%	16%	16%	28%

TABLE 15.8 Characteristics of Container Glass Recycling and Cullet End Use

	Glass Container Cullet		
	Closed Loop Market Demand	→ →	Open Loop Regulatory driven
Type of recycling	Product to product	Material to material	Material substitution
Type of use	Used in container glass production	Used in other glass production	Used in nonglass applications
Typical end products	Glass bottles	Fiber glass insulation	Aggregates and substrate
Secondary energy saving/t (batch melt)	≥1.5GJ	≥1.5GJ	0
CO ₂ emissions avoidance kg t (batch melt)	215–250	200–230	0
Maximum cullet proportion	90%	50%	10%–20%
Continual loop recycling	Yes	No	No

Sources: Enviro Consulting Ltd., 2003. "Glass Recycling—Lifetime Carbon Dioxide Emissions," British Glass Manufacturers Confederation, Sheffield; Butler and Hooper, 2005. "Dilemmas in optimising the environmental benefit from recycling: A case study of glass container waste management in the UK," *Resources Conservation and Recycling* 45, 331–355.

States the Glass Packaging Institute's 'High Quality Cullet' guide.

A key dependency for optimizing environmental benefit is the achievement of a balanced flow of material through the system. For this to happen it is essential to have the necessary capacity at each stage, without an over or under-supply of material. In practice, the different motivations of the actors in the system can, and often do, prevent this system balance being achieved and may result in open-loop recycling, for example, using cullet as a substrate in road construction. This situation arises where there is insufficient demand for cullet of a specific color and grade for glass container production. One reason for this may result from there being an imbalance between regulatory recycling targets and commercial demand.

Replacing virgin feedstock with cullet avoids the H_{chem} and H_{gas} energy use presented in Table 15.3. Based on a furnace thermal efficiency of 50%, a theoretical saving of the energy used in the glass container batch melt from 100% cullet

rather than 100% virgin feedstock would be in excess of 1.5GJt^{-1} of delivered (secondary) energy. Table 15.8 shows that, as a result of the reduction in energy use and avoidance of heat reactions with soda ash and limestone, CO₂ emissions from the batch melt are reduced by 215–250 kg t⁻¹ if a theoretical 100% cullet is used in place of virgin feedstock in container production. As there is no limit to the number of times glass can be recycled, these savings can be repeated, depending on the efficiency of the recycling regime in keeping waste container glass within the loop. Although a similar one off energy saving is obtainable from using cullet as raw material for producing fiberglass, it is not possible to then recycle fiberglass as feedstock into further production cycles [39]. At the other end of the spectrum, it has been shown that reductions in the energy burden through the use of cullet in aggregate production are largely dependent on the reduced transport resulting from using locally produced cullet rather than more distant virgin raw

materials. In some cases, using cullet may actually increase the energy burden compared to using virgin feedstock [40].

4 THE FUTURE FOR GLASS PRODUCTION AND RECYCLING

Within the glass making industry segments there have been significant energy efficiency improvements arising from two main sources—light weighting of glass containers, and the widespread installation of oxy-fuel combustion systems in furnaces.

The possibility of reducing the weight of various types of beverage and food container without any deterioration in product quality was demonstrated in a research project undertaken by WRAP in conjunction with the Co-operative Retail Group in the UK [41]. Light weighting has been implemented across many segments of glass container production, put particularly in the case of beer, where it is claimed that bottles being produced today may be half the weight of bottles produced 20 years ago [42], while significant reductions in the weight of wine bottles are also claimed [43]. Assuming the commonly quoted compound annual growth rate of 2%–3% for the production of glass container units during the years 2008–15, we calculate that global production in 2015 would have amounted to between 84 and 91×10^6 t, rather than 77×10^6 t in reported in Table 15.1, with the consequent savings in energy consumption and emissions.

Oxy-fuel combustion is the process of burning a fuel using pure oxygen instead of air as the primary oxidant. In essence, this avoids using heating the 78% of the inert nitrogen in air, with only oxygen being heated [41]. Allied to enhanced energy efficiency per tonne of glass produced there are downstream reductions in oxides of nitrogen, while the gases produced by combustion are largely CO_2 and H_2O which can be sequestered. For large efficient regenerative furnaces, it has been estimated that

energy savings would be between 5% and 20% [44–46].

In spite of the energy efficiencies outlined previously, there are clear environmental and financial benefits accruing from using glass cullet rather than virgin feedstock in glass production. Based on the data in Tables 15.1 and 15.5, we estimate that $35 \pm 5\%$ of the container glass consumed globally enters the recycling loop, leaving room for significant enhancements in recycling rates in order to meet the demand of glass container manufacturers for quality cullet. Some initiatives to enhance container glass recycling are considered as follows.

4.1 Introduction of Container Deposit Schemes

Container deposit schemes have been shown to be very effective in motivating householders to recycle food and beverage containers. Thus, the 11 US states with container deposit legislation consistently return glass container recycling rates of between 66% and 96%, compared to the 35% average for those states without such provisions [47]. Similar differences between those member states with container deposit legislation and those without are found in the European Union [48].

An enhancement to deposit schemes is the provision of conveniently located reverse vending machines, often in supermarket stores, where bottle deposits are returned once the empty has been deposited in the machine.

Regulatory systems where the target is to maximize the amount collected for recycling without the need to take into account maximizing environmental benefit may encourage the easy option of open-loop recycling. In the UK, from year 2011 the Department of the Environment, Food and Rural Affairs (DEFRA) set differentiated glass packaging recycling targets for businesses based on whether material was recycled into open- or closed-loop processes [49]. However, the challenge to meet recycling targets based on mass means that open-loop

recycling still accounts for a significant proportion of the total. From 2016 onwards the overall glass packaging recovery target is 77% by mass, split between aggregates and remelt (closed loop) in the ratio 33%:66%. The effect of this is that nearly 50% of the potential for use as cullet is still not encompassed within the recycling target.

In some countries, in order to minimize city and local government collection costs and maximize recycling, there is a move away from collecting color-separated glass containers at source, to collecting mixed color glass containers or even mixed material recycle. This passes the sorting and cleaning burden on to cullet processors. One development in overcoming the problem of mixed colored cullet is the introduction of color separation systems to identify and remove glass cullet of different colors.

4.2 Infrastructure Maintenance and Change

In the case of rapidly developing countries and regions, there will be an increasing movement from unregulated to city and local government regulated systems, financed by local taxes and other financial stimuli. During this transition, it will be important to ensure that regulatory systems take over from market-driven ones, without there being a void created by lack of financial motivation for those at the picking and sorting end of the cycle, due to the availability of better employment opportunities.

The challenge for the regulatory systems found in developed countries and regions is to ensure that all the links in the cycle from household to glass producer are in balance in terms of the flows of material through the system.

5 CONCLUSION

The core challenge for environmentally and cost-effective recycling of container glass continues to be the dispersed nature of its sources, principally households, and the consequent

need for an environmentally and cost-effective infrastructure providing for its color separation, collection, and transportation to processors to produce furnace ready feedstock. In assessing the scope for increasing the amount of glass recycled, there is an overall need to quantify the resultant energy and other environmental burdens to allow valid comparisons to be made with the burdens of using virgin feedstock. Nevertheless, based on the data in Table 15.8, overall significant environmental and cost benefits can result from substituting cullet for virgin feedstock in container glass production.

Assuming a global glass container recycling rate in the region of 35%, there is a huge potential for energy savings and resultant reduction in carbon emissions by increasing the proportion of postconsumer waste (PCW) sourced cullet used in container production. Based on the 2014 figure of 77×10^6 t of container glass produced globally, and assuming an overall 50% thermal efficiency in the batch melt, an 80% use of cullet would result in about 58×10^6 GJ of energy saved per annum compared to the energy consumed using 30% cullet. Reductions in CO₂ emissions using the same cullet/virgin feedstock ratios would be about 8.8×10^6 t per annum, based on the same assumptions. These potential reductions represent a very strong case for striving to enhance the proportion of PCW cullet used in container glass production into the future.

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End-of-Life Textiles

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OUTLINE

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1 INTRODUCTION

The basic differentiation between humans and animals is the wearing of clothing. The processing of fibers to textiles is thus one of the oldest human crafts. Since ancient times clothing has been produced as protection from cold, heat, or rain. Even today clothing represents a basic human need besides food, water, housing, sanitation, health, and public transport. At the same time, in industrialized countries the purpose of apparels has tremendously changed. Clothing as well as home textiles

have become a question of style and fashion. They are hardly disposed of because they are damaged or worn but rather because they are not in vogue. As a result, in industrialized countries there is a massive overconsumption of textile products. On the one hand, there is a positive effect on the textile industry and subsequently on employment and turnaround. On the other hand, an excessive use of resources and a large generation of waste have to be accepted. Either way we have no choice but to face the large amounts of end-of-life textiles.

2 TECHNOLOGICAL, ECONOMICAL, AND ECOLOGICAL BACKGROUND

2.1 Definitions

Textiles and fibers are closely linked together. According to the European Regulation No 1007/2011 [1] a textile product *means any raw, semi-worked, worked, semi-manufactured, manufactured, semi-made-up or made-up product which is exclusively composed of textile fibres, regardless of the mixing or assembly process employed*. The same regulation defines a textile fiber as *a unit of matter characterised by its flexibility, fineness and high ratio of length to maximum transverse dimension, which render it suitable for textile applications*. Fibers are explicitly distinguishable from rods and wires which are either too stiff or too coarse. There are no definite threshold values for length and width of fibers. Usually fibers are categorized according to the unit length [2] as presented in Table 16.1.

The cross section of fibers is not necessarily circular but frequently exhibits profiles such as angular (e.g., triangular), lobal (e.g., trilobal), serrated, oval (e.g., bean-shaped), ribbon-like, or even hollow. It is thus clear that the diameter is not a universally applicable property for defining the fineness of a fiber. In order to

circumvent this problem it is well established in the textile industry to use the fiber denier (i.e., the linear density) [3]. The mass of a certain length of a fiber or a yarn is usually given in terms of a “tex” unit (1 tex = 1 g per 1000 m), or a decitex (dtex = 1 g per 10,000 m) or a denier (1 den = 1 g per 9000 m [4]).

Fibers are composed of a variety of materials but are usually categorized into natural and man-made fibers as sketched in Fig. 16.1. Natural fibers comprise crop as well as animal fibers. Within this group, cotton (a crop fiber) is the most important. Man-made fibers are classified according to their chemical composition, with the most fundamental differentiation being between organic and inorganic materials. Within organic man-made fibers there is a distinction between polymers from natural resources, mainly cellulose (i.e., cellulose) and from synthetic polymers originating from petroleum (i.e., synthetics). Fig. 16.1 shows the major fiber categories including representative examples.

The use of fibers and fiber-containing goods is widespread. The main end applications comprise apparel, home furnishing, and industrial uses. Apparel is basically subdivided into outerwear (e.g., trousers, coats, dresses) and underwear (e.g., briefs, stockings, undershirts). Home furnishing comprises carpets and other home textiles such as curtains, blankets, or table-clothes. The category of industrial uses is extremely diverse. Inter alia areas such as protective end uses; building and construction; medical, pharma, and health; and filter media and membranes have to be mentioned. Since fibers can be found in a great variety of products, it is to be expected that fibers end up in diverse waste streams.

TABLE 16.1 Definitions of Fiber-Related Terms Ranked With Decreasing Unit Length [2]

Term	Definition
Filament	A fiber of very great length; considered as continuous
Staple fiber	A textile fiber of limited but spinnable length
Flock	Very short fibers intentionally produced for other purposes than spinning
Fiber fly	Airborne fibers or parts of fibers (light enough to fly), visible as fibers to the human eye
Fibril	A subdivision of a fiber; can be attached to the fiber or loose

2.2 Fiber Market

Worldwide fiber production reached 90.6 million tons (90.6×10^6 t) in 2015 [6] as sketched in Fig. 16.2. Synthetic fibers make up 69% (i.e., 62.9×10^6 t) of all fiber production. Within this group polyester fiber is the most important,

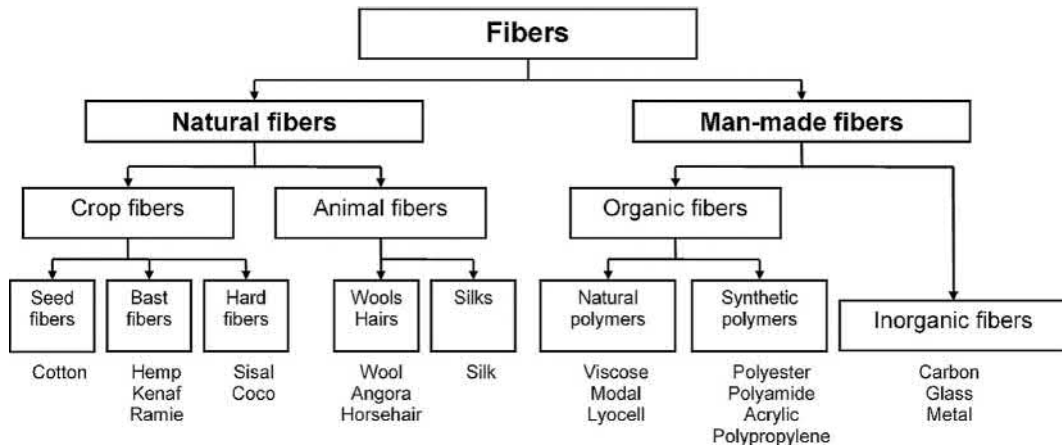


FIG. 16.1 Categories of the most important fibers [2, 5].

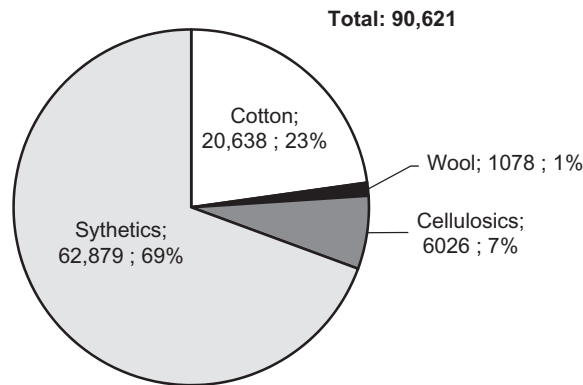


FIG. 16.2 Production of fibers (in 10^3 t and mass %) in 2015 by category [6].

amounting to about 83% (52.1×10^6 t) of all synthetic fibers. Cellulosic fibers exhibited a distinct increase and in the time period 2005 to 2015 the production rate almost doubled from 3.2×10^6 t (i.e., 4.8% of total fiber production) to 6.0×10^6 t (i.e., 6.6% of total fiber production). Cotton represents the most important natural fiber showing a share of 23% (i.e., 20.6×10^6 t) compared to all types of fibers. The production rate for cotton fluctuated between 19.1 and 26.9×10^6 t over the past 15 years as a result of fluctuating supplies which depended in turn on the growing conditions. As synthetic fibers, mainly polyester, showed an increase over the past decade,

the share of cotton decreased from 37% in 2005 to 23% in 2015. Other natural fibers are of less commercial importance (e.g., wool: 1.2% or 1.1×10^6 t).

Table 16.2 again shows that polyester is by far the most important fiber type. It is also evident that China holds a predominant position in fiber production as it holds 66% of the worldwide market. Europe and the USA are of minor importance. But, Europe still holds 50% of olefin fiber production, even if this category exhibits a relatively small volume.

It has to be pointed out that the European Man-Made Fibres Association (CIRFS) statistics

TABLE 16.2 Fiber Production (World, China, Europe, USA) in 2015 by Fiber Type [6]

Fiber Type	World [1000t]	China		Europe		USA	
		[1000t]	[%]	[1000t]	[%]	[1000t]	[%]
PAN	1804	703	39.0	515 ^a	28.5	–	0.0
PA	4511	2369	52.5	447	9.9	557	12.3
PET	52,146	37,477	71.9	1056	2.0	1283	2.5
Olefin	3183	334	10.5	1618	50.8	311	9.8
Others	1253	693	55.3	268	21.4	120	9.6
Total	62,897	41,576	66.1	3904	6.2	2271	3.6

^a Data for 2014.

are mainly based on man-made fibers with cotton and wool as competitor. There are numerous other natural fibers in the market of which jute is the only one of relevance. In 2011/12 the worldwide production of jute was about 3.2×10^6 t [7]. In the same period, the total volume of natural fibers other than cotton and wool did not exceed 3.5×10^6 t [7].

It is expected that fiber production will increase significantly in the future. The two main reasons for that are as follows: on the one hand, world population is steadily growing creating an increase in fiber demand; and on the other hand, overall worldwide prosperity is predicted to increase, especially in many emerging marks, and this is closely linked to fiber consumption (i.e., increasing consumption per capita). It can further be assumed that, with a certain time delay, a comparable amount of fibers will end up as waste. Thus we can expect the fiber portion in waste to increase over the next few years.

2.3 Fiber Production

Natural fibers, among which cotton is of major importance, are renewable products. During their growing stage, cotton plants absorb carbon dioxide from the atmosphere. But, cotton cannot be seen as a sustainable product as a significant quantity of energy, vast amounts of agricultural chemicals, and enormous amounts of

water for irrigation are required to grow the cotton [8, 9]. Furthermore, crop land for cotton production is in competition with food production. Cotton production seems to have reached a platform and a further increase is not expected to take place. Cellulosic fibers are man-made fibers but use natural polymer cellulose as a raw material. Thus to a certain extent, cellulosic fibers are renewable. The production process, however, requires a significant amount of energy and resources. Synthetic fibers are based on petroleum and are a priori not sustainable. Petroleum is not only used as feedstock but also as source for energy in polymer production and fiber manufacture. The overall energy consumption is, thus, higher than that compared to cotton or cellulosic fiber production. Figs. 16.3 and 16.4 compare the energy and water consumption for the production of relevant fibers [10]. The energy involved ranges from 60 GJ t^{-1} (cotton) to 175 GJ t^{-1} (acrylic fiber). In terms of water consumption used in the production of different fibers, values of between $32 \text{ m}^3 \text{ t}^{-1}$ (high density polyethylene fibers) and $663 \text{ m}^3 \text{ t}^{-1}$ (polyamide 66 fiber) are reported. Cotton falls totally out of the series as it consumes about $66,000 \text{ m}^3 \text{ t}^{-1}$. It has to be pointed out that the actual energy and water consumption and the ratio between renewable and nonrenewable energy are strongly dependent on the particular situation of the production site [8].

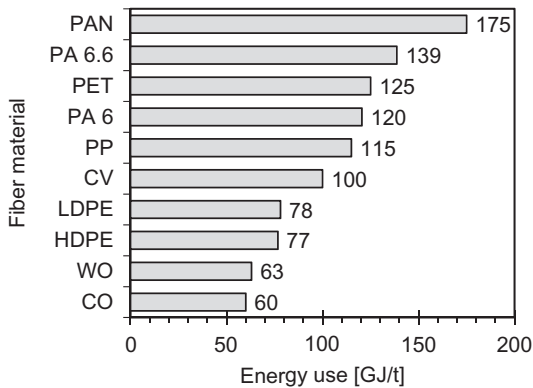


FIG. 16.3 Energy requirement for fiber production [10]. Abbreviations of fiber materials according to Refs. [2, 11].

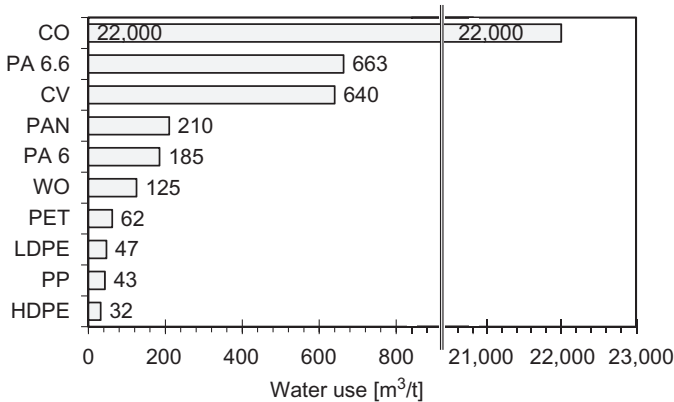


FIG. 16.4 Water consumption for fiber production [10]. Abbreviations of fiber materials according to Refs. [2, 11].

2.4 The Textile Processing Chain

Fibers represent an intermediate or semifinished product. Depending on the final end use, fiber processing can take many forms. Basically, one can distinguish between conventional textiles manufactured from yarns and nonwovens. The classical route comprises spinning (yarn making) and weaving or knitting resulting in woven or knitted fabrics. Alternatively, nonwovens are formed directly from individual fibers. Certain applications do not require fabrics but yarns, rovings, or fibers. Table 16.3 presents typical energy consumption for different types of garment [12, 13].

TABLE 16.3 Consumption of Energy for Garment Production [12, 13]

	Cotton	Polyester	Viscose	
Production Step	Energy/GJt ⁻¹			
Fiber production	55	64	126	173
Preparation/blending	29		29	
Spinning	89		90	
Knitting	32	96	49	68
Dying/finishing	27		27	
Making up	9		9	
Total/GJt ⁻¹	241	160	330	241

Dyeing and finishing are usually carried out in the wet state. Thus not only the energy consumption is relevant but additional water is required (144 and $380 \text{ m}^3 \text{ t}^{-1}$; [14]) and furthermore, large amounts of waste water arise.

3 TEXTILE WASTE TREATMENT SCENARIOS

3.1 Overview

As outlined in Section 2.4 fiber processing from the start to the final product takes a long time and consumes large amounts of energy. Fig. 16.5 sketches roughly the textile processing chain and also includes the energy

consumption. The arrow on the left side outlines the energy involved along the processing path. As indicated by the arrow on the right side, it is thus preferable to find routes for reuse or recycling which take place at a stage in the process after the most energetic steps have been taken (maximum depth of processing) or which are located on the bottom of the diagram.

End-of-life textiles account for waste and usually are covered by a more or less developed waste management system. In the EU waste management is largely based on the waste framework directive (WFD) which has introduced a priority order for waste, the so-called waste hierarchy as sketched in Fig. 16.6 [16].

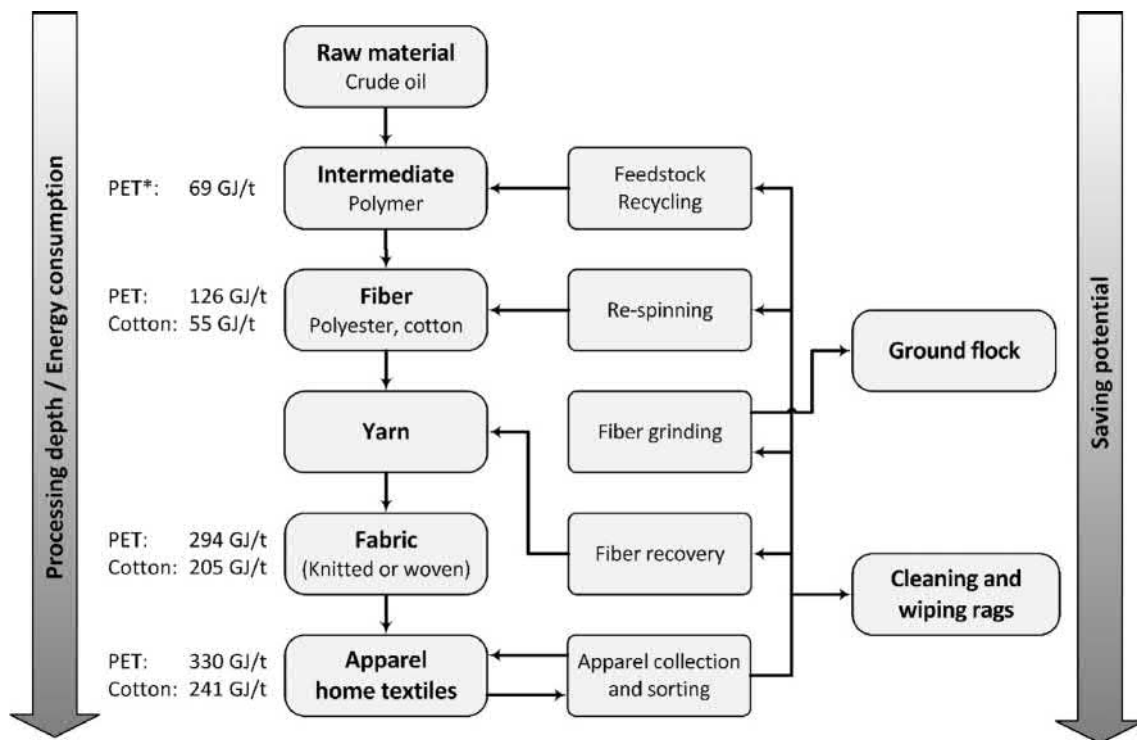


FIG. 16.5 Scheme of textile processing chain including possible reuse, recycling and recovery routes for cotton and polyethylene terephthalate (PET); References for energy consumption: [13]; *[15].

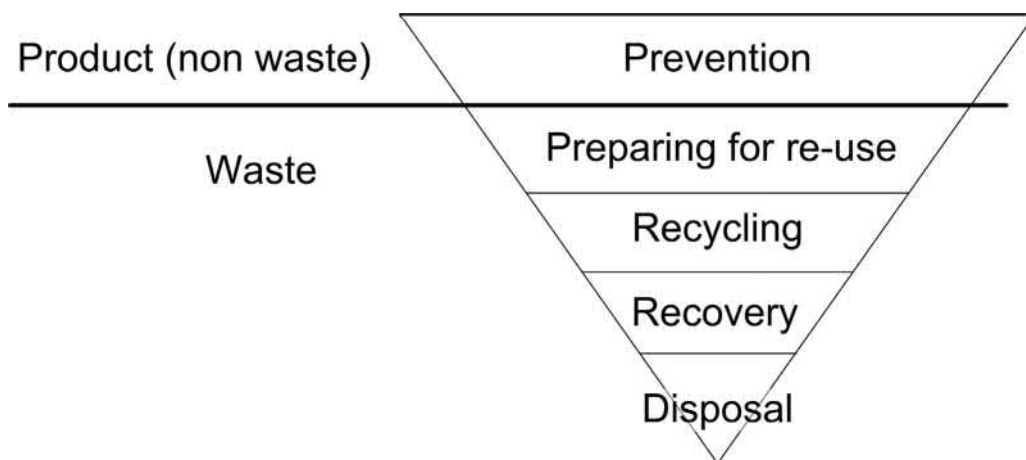


FIG. 16.6 Waste hierarchy according to the EU waste framework directive [16, 17].

3.2 Collection

For any reuse and recycling of textile waste, a waste collection separate from other types of waste is essential. Otherwise textiles could pick up moisture or dirt which would hinder further reuse and recycling processes. Secondhand clothes must be dry, clean, and not worn. Energy consumption of waste collection is mainly dependent on the population density. For household waste, a consumption of diesel of up to 10 L t^{-1} [18] is reported which corresponds to about 0.35 GJ t^{-1} . The total energy demand for end-of-life textiles (including transport, sorting, packing, etc.) is of the order of 6 GJ t^{-1} [13]. The energy requirement for secondhand clothes is, thus, negligible compared to the effort in its production (up to 330 GJ t^{-1}).

Separate collection of packaging waste is usually funded by the so-called Extended Producer Responsibility (EPR). It means that the producers must also include the management of their packaging after the product has been used by consumers. It is reported that producers pay $\text{€}3.1 \times 10^9$ (3.1 billion Euros) in annual fees for packaging EPR schemes [19]. Textiles are usually not covered by EPR schemes and are funded by the revenues from

secondhand clothes. As a matter of fact, collection rates are not as high as for packaging waste. As outlined in Table 16.4, Germany exhibits the highest collection rate (74%) of all countries.

3.3 Waste Prevention

Waste prevention is the highest ranked option in the European waste hierarchy. According to the WFD the extension of the life span of products is defined as waste prevention. Table 16.5 presents the useful life for categories of textiles in 1998 and in 2005. It is evident that all types of textiles showed a more or less distinct decrease in the useful life between 1998 and 2005. Even if legislation aims to reduce the amount of waste by the extension of the life span of products, in reality, for textiles, the trend is in the opposite direction.

3.4 Reuse

According to the EU waste hierarchy [16] reuse is a more favorable option than recovery or recycling. Multiple utilization of apparel and textiles is quite common with a washing or

TABLE 16.4 Amount of Collected Postconsumer Clothing and the Collection Rate (Collected Amount in Relation to Amount Put on Market) for Selected Countries

Country	Year	Collected Amount of End-of-Life Clothing/		Reference
		(1000t)	(mass %)	
Germany	2013	1011	74	[20]
Denmark	2010	35	48	[21]
Finland	2010	25	39	[21]
UK	2008	523	24	[22]
Sweden	2010	26	22	[21]
USA	2013	15,130	15	[23]

TABLE 16.5 Useful Life of Different Categories of Textiles in 1998 and 2005 in Years

Category	1998 Useful Life Time	2005 Useful Life Time	Decrease of Useful Life/%
Stockings/tights	1.4	1.0	28.6
Briefs/underpants	2.1	2.0	4.8
T-shirts/polos	2.6	2.0	23.1
Jeans	3.0	2.0	33.3
Blouses/shirts	3.4	2.5	26.5
Trousers other than jeans	3.7	2.0	45.9
Tracksuits	3.8	2.0	47.4
Pullovers/cardigans	4.0	2.5	37.5
Towels/bath towels	5.4	4.0	25.9
Dresses/suits	5.6	3.8	32.1
Coats	6.5	4.2	35.4
Bed linen	7.4	6.0	18.9
Table linen	9.3	6.0	35.5
Blankets	10.0	8.0	20.0
Curtains	10.8	6.5	39.8
Carpets	11.5	7.3	36.5

The percentages show the values of 2005 in relation to 1998 [20].

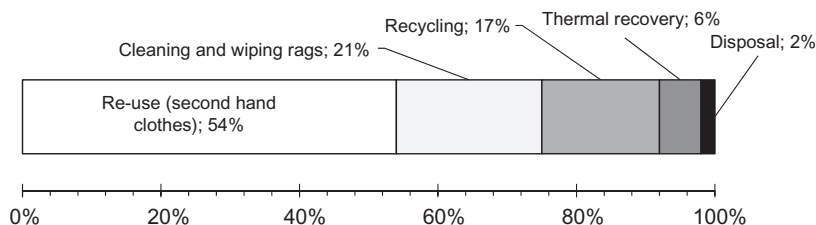


FIG. 16.7 Main uses of fractions obtained by sorting of end-of-life textiles in Germany [20].

cleaning step after each cycle. In these cases reuse means a further utilization after the primary customers have sold or given away the product.

It has been outlined before that a separate collection of end-of-life textiles is a prerequisite for any reuse. As a first step after collection a sorting of the textiles is required. The collected items are sorted into different fractions according to products group, material, or color. In Germany on average 154 fractions are obtained [20]. As demonstrated in Fig. 16.7 only about half of the collected items are feasible for reuse. Some items are dirty, worn or damaged, and are only feasible for other less economic uses.

Among the fraction suitable for reuse, typically 1% to 3% of the items are fully functional and correspond to current fashion trends. These textiles can be sold in secondhand shops in industrialized countries for about $\text{€}10,000\text{t}^{-1}$ [12]. The major fraction of rewearable textiles is sold for prices between $\text{€}900$ and $\text{€}1400\text{t}^{-1}$ [24].

Frequently, secondhand clothes are exported to African countries and there is an ongoing discussion about the effects on the textile industry in developing and emerging countries. On the one hand, it is reported that secondhand clothes have caused an enormous decrease in the activities within the local textile industry [25]. On the other hand, in many sub-Saharan countries people cannot afford new clothing and secondhand clothes can generate jobs for trade, distribution, repair, restyle, and washing [26]. It is evident that secondhand clothes show the highest saving potential (up to 330GJt^{-1} ; see Table 16.3). Nevertheless, it has to be considered that all

textiles will sooner or later reach the end-of-life state and that African countries have no proper waste management.

3.5 Recycling

3.5.1 Cleaning & Wiping Rags

In a broader sense the reuse of fabric can be seen as component reuse. In contrast to second-hand clothes it is also convenient for worn and damaged apparel as well as for production rejects, which arise in the course of garment making, to be used for cleaning and wiping rags. The saving potential is relatively high as the production of the fabric would have required a considerable input of energy of up to 294GJt^{-1} . In practice, when fabric or nonwoven textiles are reused, they are used as cleaning rags.

The requirements for cleaning rags are reasonably high. Ideally they should consist of cotton, linen, or viscose with minor portions of synthetic material and should be either white or colored [27]. However, textiles with a high fraction of synthetic material can be used as oil absorbent rags [28]. Heavy and hard constituents such as carpet residues, fastenings, eyelets, or zippers must not be present. In practice, a minimum size of $20 \times 30\text{cm}$ is required [27]. The market price of cleaning rags is relatively high and ranges between $\text{€}1200$ and $\text{€}1600\text{t}^{-1}$ [24]. However, the manufacture of cleaning rags demands a high input of man power and due to the high personnel cost in developed countries such as in Europe, the overall economic situation for cleaning rags is rather poor.

3.5.2 Fiber Recovery

Fiber recovery refers to fibers that are derived from end-of-life apparel, fabrics, or rejects arising in the course of the textile processing chain. Fiber recovery is a rather complicated process and product quality is significantly reduced. Since the fibrous structure is maintained and reused the saving potential is higher than for respun fibers and ranges between 55 (cotton) and 126 GJ t^{-1} (polyester).

The conventional process, to disintegrate textile structures and yarns, uses equipment such as cylinder raising or “fearnought” opener machines. In the process, unwanted and damaged fibers are separated and finally the recovered fibers are obtained. The process is, however, damaging to fibers. In particular, fiber length is drastically reduced, and only 25% to 55% of the fibers are longer than 10 mm [29]. Furthermore, the material contains a considerable portion of dust as well as residual yarns. Fiber length distribution is wide and commonly recovered fibers are a blend of various fiber types. As a result the recovered fibers exhibit a significantly lower level of quality than do the virgin products. To a certain extent the recovered fibers can be used for technical textiles as well as for nonwoven materials [29, 30]. Generally, fiber recovery in industrial countries, such as the EU, is in competition with low cost imported textiles from Asia, and as a result textiles from recycled fibers are becoming increasingly less competitive and less important.

Apart from the classical textile disintegration process discussed above, it is reported that an alternative method can result in fibers showing properties similar to new fibers [31, 32]. In particular fibers up to 30–40 mm length can be obtained. However, the processing costs are high and the process is only convenient for high value fibers such as Aramid polymers.

3.5.3 Respinning

The respinning of fibers refers to the process involved when a polymer, for example, polyester, is melted (or dissolved) and new fibers or

filaments are produced. Even if the fiber quality is similar to the quality of fibers from the original material, this procedure shows two main disadvantages. On the one hand, the fibrous structure is destroyed and as a result this recycling route corresponds to *material recycling* (see Section 1) and the amount of energy saved is low since the energy required for fiber formation has to be repeated. For polyester, only 81 GJ t^{-1} instead of 126 GJ t^{-1} can be saved. On the other hand, very often the secondary polymer, such as polyester, does not originate from fibers but from other products. In practice a so-called plastic “bottle to fiber” principle is realized. It means that secondary polyester from bottles is used to produce filaments or staple fibers [33, 34]. Although recycled polyester shows reduced material properties such as molecular weight, it can be blended with virgin material resulting in comparable fiber qualities [35]. In practice however, a “fiber to fiber” recycling procedure is not usually viable because the recycled fiber material commonly consists of a blend. A selective dissolution of certain polymers out of a mixture is possible but at present the procedure is only used for laboratory and analytical purposes [36]. In conclusion, the production of respun fibers is uneconomical.

3.5.4 Fiber Grinding

The potential sources for ground fibers are widespread. Feedstock for ground fibers includes apparel which are torn or damaged, rejects from the textile processing chain, or even alternative fiber containing waste such as fluff from end-of-life tires. In regard to material originating from apparel sorting, fiber grinding results in an almost complete spectrum of fractions and thus the portion of waste is significantly minimized.

Ground fibers are similar to ground flock and thus not convenient for spinning (Table 16.1). One can distinguish between cut and ground flock. On the one hand, cut flock requires a guillotine cutter, exhibits a uniform fiber length, and

is exclusively manufactured from filaments. On the other hand, ground flock shows a rather broad distribution of fiber length and can be produced from any staple fiber by a grinding process. It is well established that ground flock can be used as a reinforcement or viscosity modifiers. For instance, ground cellulose is frequently applied as additive to bitumen in order to increase the load capacity and temperature resistance of asphalt pavement material [37].

Since ground flock allows a rather broad fiber length distribution, it is usually made from end-of-life fiber products. Since the grinding machinery is very sensitive toward metallic and hard components it has to be ensured that all unwanted and potentially damaging bits and pieces are separated and removed. The feasibility of the process has already been shown for fibers derived from end-of-life tires. And such fibers have been successfully used as an additive in bitumen instead of the well-established ground cellulose [38]. Apart from tire-derived fibers it is also reported that the nonrecoverable fraction from apparel collection (see Table 16.6) can be processed to a short fiber product to be used in bituminous and cementitious construction materials [39, 40]. Ground fibers derived from textiles and other fiber containing waste seem an interesting recycling option, not only from an ecological but also from an economical point of view. Ground fibers and recycled fibers have been successfully introduced into many markets.

3.5.5 Feedstock Recycling

As sketched in Fig. 16.5 polymer waste such as polyester [41] can be used as chemical feed stock. It is reported that polyester fibers can be converted to bis(2-hydroxyethylene terephthalate) monomer by glycolysis [42] to be used for fiber production or, alternatively, for the manufacture of textile dyestuffs [43]. Even if procedures are technically viable it has to be questioned whether it is ecologically and economically worthwhile. On the one hand, the waste polymer competes with intermediates from petroleum and, thus, the saving potential is fairly low. On the other hand, waste, in particular fibrous waste, is commonly contaminated with a variety of extraneous materials (e.g., other polymers, textile auxiliaries) which complicates the processing scheme. Fiber recovery and not polymer recycling seems to be the more favorable option from both an ecological as well as from an economical point of view.

3.6 Incineration and Landfill

Incineration of textile waste materials can at least recover a certain fraction of the caloric value consumed for its production. In comparison to the energy used for fiber production, the reclaimable energy is quite low as presented in Table 16.6. The balance is even worse when considering the energy consumed for garment production. The fraction of reclaimable energy is

TABLE 16.6 Energy Required for Fiber and Garment Production and Energy Reclaimable by Incineration Assuming an Energy Efficiency of 60% [8, 12]

	Production Energy/GJt ⁻¹			Reclaimable energy/%	
	Fiber	Garment	Caloric Value	Fiber	Garment
Cotton	36	241	17	28	4.2
Polyester	93	330	23	15	4.2
Viscose	19	285	17	54	3.6

around 4% only. It is clear that incineration exhibits advantages over landfill, but any other reuse or recycling option is favorable from an ecological as well as from an economical point of view.

Landfill represents the least favorable option of waste treatment. In spite of this, a large portion of waste and also end-of-life fibers are presently disposed of in this way. Because most fibers are not biodegradable (synthetics) and also because of the high energy that has gone into production, landfilling of textiles and fibers should be avoided whenever a viable alternative exists.

4 DISCUSSION

As shown before, a variety of methods does exist for treating waste and end-of-life textiles. It is of interest to investigate the driving forces to avoid landfilling or incineration in favor of recycling and reusing textile and fiber waste.

Legislation plays an important role in the treatment of waste. For instance, the minimum recycling quotas as required by the EU directive on end-of-life vehicles [44] have initialized a great push to develop new methods and procedures. Of course, the treatment of textile waste is also significantly influenced by regulations such as the deposition ban for untreated waste in Germany and Austria.

Economy is also an important driving force in determining the direction followed by waste streams. If the economy of the recovery process is advantageous the processes will run without intervention such is the case with the recovery of noble metals. On the other hand, even if legislation dictates recycling quotas, waste can be directed to illegal routes if no economically viable procedures for recycling and recovery are available. For instance, it has been reported that up to 75% of end-of-life vehicles are illegally exported from the EU countries [45] and, thus,

circumventing the stringent European waste legislations.

From an economical point of view, textile waste exhibits an exceptional position. As outlined in Section 3.2 textiles are commonly not subject of EPR schemes but are funded by the profit obtained by the sale of secondhand textiles. It is thus the scope of textile collectors to focus on clean and fully functional items as other options than secondhand clothes are not economically attractive. A compulsory EPR scheme for textiles and clothing could force collectors to go for all categories of textile waste, even worn and dirty items.

Finally, environmental and ethic attitudes can significantly influence waste treatment. Textiles represent a basic need for all human beings either as simple covering or as protection against cold. However, in industrialized countries textiles are frequently discarded and changed due to fashion reasons even if the products are almost new and fully functional. For ethical reasons many people in the industrialized countries do support the idea of secondhand textiles and thus, in the field of apparel collection, charity organizations as well as public and commercial organizations are well established to deal with the reuse of textiles and secondhand clothing. This is unique in the area of waste disposal and waste management.

Today regional markets are steadily losing their importance and global markets are influencing world economy. This development is particularly true for textiles. Asia plays a predominant position in the textile industry and industrialized countries such as the EU can only keep up with speciality products. The EU stringent regulations for waste, also valid for textile waste, only affect a small share of the total textile volume. Production residues or rejects primarily arise in Asia and are thus not affected by EU legislation. A high degree of reuse and recycling will only affect end-consumer products imported to the EU but not the majority of the textile industry. This is not only valid for textile

waste but also for the by-products of the textile processing industry such as waste water [46] and textile chemicals [47].

In the European Union waste management is currently undergoing significant changes. In December 2015 the EU Commission has launched the so-called Circular Economy Package [48]. Several documents suggest amendments of waste-related directives in the near future. Textile waste is not directly addressed but the landfill directive should be amended in a way that the fraction of municipal solid waste to be landfilled is restricted to 10% [49]. This will boost activities to divert waste, including textile waste, from landfill to incineration or recycling.

The circular economy package goes beyond recycling. Member states should promote reuse activities or give support for reuse and repair networks [50]. The Commission will also prepare an independent testing program on issues related to possible planned obsolescence practices [51]. In view of the fact that textile items are frequently of poor quality and used textiles are hardly suitable for repair, these initiatives by the Commission might exert a strong pressure on textile producers, importers, and retailers.

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Chemicals in Waste: Household Hazardous Waste[☆]

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1 INTRODUCTION

“Household hazardous waste” (HHW) is a term used to describe hazardous wastes entering the municipal waste stream. It represents a variety of waste types classified together based on the possession of hazardous properties. Although various national classification systems exist, either legislatively imposed or as voluntary schemes, that categorize the relevant household

products in a hazardous subcategory of municipal waste, separate collection is rare in many countries, with the result that such products are generally discarded alongside nonhazardous household waste. This chapter looks at the problems related to the disposal of chemicals and other hazardous substances used in the home. Examples of chemical HHW are shown in Fig. 17.1.

2 SOURCES OF HHW

Hazardous products at home are a diverse and variable group categorized together due to their hazardous properties (see Boxes 17.1A

[☆] This chapter has been updated by TML from the chapter in the 1st edition written by Rebecca Slack and Trevor M Letcher.



FIG. 17.1 Typical household products with potentially hazardous properties.

and 17.1B). Common items considered to possess such hazards are household cleaning products (oven cleaners, household bleach, etc.; Table 17.1); garden pesticides (insecticides, fungicides, and herbicides); paint and wood preservatives; mineral oils and oily substances, including motor fuels and lubricants; inks and dyes; pharmaceuticals; photographic chemicals and processing materials; swimming pool cleaners; heavy metal containing products (fluorescent lamps that contain mercury; end-of-life vehicles containing oils, asbestos, antifreeze, etc.; electrical and electronic equipment with refrigerants); and batteries. Lists of household hazardous products vary from country to country and region to region depending upon chemicals permitted for use in products. For instance, the REACH regulations in the European Union (EU) require that each chemical produced or

used in the EU in amounts over 10,000 tons (1×10^4 t) is thoroughly examined for effects on health and the environment, helping to flag potentially harmful substances. Nevertheless, it has been suggested that the average household in many parts of the world (e.g., United States or Europe) contains about 50 kg of toxic material [1]. A list of potentially hazardous household chemicals is given in Table 17.1.

Not all household hazardous products such as a desktop computer or energy-saving light bulb are immediately dangerous to human health and the environment. However, a number of chemical products such as household cleaners can be dangerous to particular population groups and/or environmental compartments. Children and pets are vulnerable to poisoning from direct exposure to such products. A number of reports indicate that toilet

BOX 17.1A

PROPERTIES OF PRODUCTS/WASTES THAT RENDER THEM HAZARDOUS TO HUMAN HEALTH AND THE ENVIRONMENT [46]

- Explosive—substances and preparations that may explode under the effect of flame or are more sensitive to shocks or friction than dinitrobenzene.
- Oxidizing—substances and preparations that exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
- Highly flammable—liquid substances and preparations having a flash point below 21°C (including extremely flammable liquids); or substances and preparations that may become hot and finally catch fire when in contact with air at ambient temperature without any application of energy; or solid substances and preparations that may readily catch fire after brief contact with a source of ignition and may continue to burn or to be consumed after removal of the source of ignition; or gaseous substances and preparations that are flammable in air at normal pressure; or substances and preparations that, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.
- Flammable—liquid substances and preparations that have a flash point equal to or greater than 21°C and less than or equal to 55°C.
- Irritant—noncorrosive substances and preparations that, through immediate, prolonged, or repeated contact with the skin or mucous membrane, can cause inflammation.
- Harmful—substances and preparations that if inhaled or ingested or penetrate the skin may involve limited health risks.
- Toxic—substances and preparations (including very toxic substances and preparations) that if inhaled or ingested or penetrate the skin may involve serious, acute, or chronic health risks and even death.
- Carcinogenic—substances and preparations that if inhaled or ingested or penetrate the skin may induce cancer or increase its incidence.
- Corrosive—substances and preparations that may destroy living tissue on contacts.
- Infectious—substances that contain viable micro-organisms or toxins that are known or reliably believed to cause disease in man or other living organisms.
- Teratogenic—substances and preparations that if inhaled, ingested, or penetrate the skin may induce nonhereditary congenital malformations or increase their incidence.
- Mutagenic—substances and preparations that if inhaled or ingested or penetrate the skin may induce hereditary genetic defects or increase their incidence.
- Substances/preparation that release toxic or very toxic gases in contact with water, air, or an acid.
- Substances/preparations capable by any means, after disposal, of yielding another substance, for example, a leachate, which possesses any of the characteristics listed before.
- Ecotoxic/dangerous for the environment—substances and preparations that present or may present immediate or delayed risks for one or more sectors of the environment.

BOX 17.1B

European Chemicals Bureau (ECB) hazard symbols according to European Union's Dangerous Substances Directive 67/548/EEC and used on packaging for consumer products with potentially hazardous properties.



Toxic (T)



Highly toxic (T+)



Explosive (E)



Eco hazard (N)



Harmful (Xn)



Irritant (Xi)



Corrosive (C)



Oxidising (O)



Flammable (F)



Highly flammable (F+)

cleaners, chlorine bleach, glass/window cleaners, roach killers, oven cleaners, drain openers, other cleaning products, personal care products, and pharmaceuticals are responsible for most cases of household poisoning incidents around the world—some of which prove to be fatal [2–4]. Localized environmental pollution incidences can also result from the inappropriate use of pesticides, wood preservatives, and other chemicals, although it is usually the disposal of these chemicals that realize the greatest risk. Labeling on packaging will help householders to identify potentially hazardous products. However, if householders are not aware

of the reasons behind the hazardous status, it is possible that they may not take steps to limit their exposure to any dangerous properties possessed by the product or waste, and may not be fully aware of the environmental consequences arising from inappropriate use and disposal.

3 TYPES AND QUANTITIES OF HHW

When a potentially hazardous household product is discarded, it becomes household hazardous waste (HHW). Attempts to quantify and

TABLE 17.1 Examples of Potentially Hazardous Chemicals Found in Households

Product	Ingredient	Hazardous Property
Oven and cleaners	Sodium hydroxide and/or ammonium hydroxide (ammonia), and possibly methylene chloride	Very corrosive and can cause death if ingested, burns skin and eyes
Drain cleaners	Concentrated sodium hydroxide (can be solid or in aqueous solution of 50% m/m), or hydrochloric acid or sulfuric acid (up to 70% m/m)	Very corrosive and can cause death if ingested, burns skin and eyes
Household bleach	Sodium or calcium hyperchlorite in concentrations up to 10% m/m, or hydrogen peroxide	Can burn skin and eyes
Toilet bowl cleaners	Hydrochloric acid or sodium hyperchlorite and if colored blue can contain chromium compounds	Very corrosive and can cause death if ingested, burns skin and eyes
Mold and mildew cleaners	Sodium hyperchlorite and formaldehyde	Very corrosive and can cause death if ingested, burns skin and eyes
Other cleaning products	Ammonium hydroxide (ammonia) and ethanol, chlorinated phenols and complex phosphates	Harmful if ingested and can cause burns to the skin and eyes
Air fresheners	Formaldehyde or phenol	Harmful if ingested and can cause burns to the skin and eyes
Pesticides	Organophosphates and chlorinated compounds such as chlorinated pyrethrums	Death on ingestion
Pharmaceuticals	Cytotoxic/cytostatic, antibiotics	Carcinogenic, teratogenic, risk of overdose, and so on
Paints and related products	Alcohol, glycols, ethers, ketones, toluene, xylene, acetone, esters, ketones, petroleum distillates, and solvents	Organic compounds can cause lung and kidney damage
Antifreeze	Ethylene glycol	Fatal if swallowed. Affects the central nervous system
Pool chemicals	HCl and NaOCl	Very corrosive and can cause death if ingested, burns skin and eyes

characterize HHW have proved to be difficult. The complexity of separating each hazardous product from the general waste stream for individual group quantification has restricted many researchers to comparisons of cumulative hazardous content to nonhazardous municipal solid waste (MSW). Characterization is also fraught with complications as workers use different classification systems for HHW. The European Commission provides one example of a hazardous waste list that includes some household products. This is provided by the European Waste Catalogue (EWC), Decision

2000/532/EC as amended by Council Decisions 2001/118/EC, 2001/119/EC, and 2001/573/EC, which is a list of waste descriptions, divided into 20 chapters, the last of which concerns municipal waste [5]. In the final [Chapter 14](#) waste descriptions are marked as hazardous, but only 11 describe a particular waste product ([Table 17.2](#)). Solvents, acids, and alkalis are listed without further clarification; many household cleaning agents will fall within these categories. A number of household products are not specifically included in this list, namely, personal care products (including cosmetics),

TABLE 17.2 Municipal Hazardous Waste Listed in Chapter 20 of the European Waste Catalogue [5], Notified in the List by an Asterisk

Waste Category	Six-Digit Waste Specific Code
Solvents	20 01 13
Acids	20 01 14
Alkalines*	20 01 15
Photochemicals	20 01 17
Pesticides	20 01 19
Fluorescent tubes and other mercury-containing waste	20 01 21
Discarded equipment containing chlorofluorocarbons	20 01 23
Oil and fat other than those mentioned in 20 04 25	20 01 26
Paint, inks, adhesives, and resins containing dangerous substances	20 01 27
Detergents containing dangerous substances	20 01 29
Cytotoxic and cytostatic medicines	20 01 31
Mixed batteries and accumulators containing batteries or accumulators included in 16 06 01, 16 06 02 or 16 06 03	20 01 33

The four-digit prefix, 20 01, indicates separately collected fractions.

* "Alkalines" are referred to as a category within the EWC but the more correct terminology should be "alkalis."

nonheavy metal containing batteries, medicines and veterinary products beyond the cytostatic and cytotoxic categories, aerosols, and bottled gas products.

As HHW is an extremely variable waste stream compared to other MSW streams, attempts at quantification have met with mixed success. Each of the HHW subcategories is produced in very different amounts, by mass, due to very variable composition, initial mass, and product usage patterns. Thus, by mass, waste electrical and electronic equipment (WEEE) is the greatest component of HHW and hence disguises the true scope of HHW. Although WEEE has been estimated to be produced in quantities ranging from 200,000 tons per annum to over 900,000 tons per annum in the United Kingdom and chlorofluorocarbon (CFC)-containing waste at over 1.6×10^5 t combined estimates for the remaining HHW categories varies from 2×10^4

to 2.5×10^5 t a⁻¹ depending upon the waste types considered [6–10]. One estimate assumes that each household in developed countries disposes 3.5 kg of HHW per annum [11]. Slack et al. [12] report a study that included nine HHW categories (as defined in EU legislation) and estimated that these nine categories contribute 1×10^5 t a⁻¹ to the MSW stream in the United Kingdom; the study notes that some of the categories contain products with negligible hazardous content such as water-based paints (compared to the more hazardous solvent-based paints). Generally as a proportion of MSW, estimates vary from 0% to 4% with inclusion of WEEE or 0% to 1% for all other HHW categories [13–17]; this value is fairly consistent across North America and Europe. If adequate collection facilities and disposal mechanisms are to be provided, more accurate estimates will be needed.

4 COLLECTION AND DISPOSAL ROUTES

Recent quantification studies have also looked at HHW disposal pathways. It has been estimated that almost 50% of the HHW stream is likely to be codiscarded with general, nonhazardous household waste in the general household bin, so forming part of MSW [12, 18]. Internationally, almost 70% of MSW is disposed of to landfill [19, 20]; the remaining fractions are disposed of through incineration, energy from waste incineration, recycling, and reuse. Much of the remaining HHW (about 45%) is discarded at household waste reception centers (HWRCs) or collected from homes. Discarding HHW items at HWRCs or having a separate collection from households need not imply that the items are separately collected; householders may not necessarily be aware of the operation of oil, paint, and battery collection banks and hazardous waste safes, simply placing the items in the general household waste receptacle. In the EU, WEEE is also separately collected as is equipment containing ozone-depleting substances as required by legislation. Increasingly, however, improved accessibility and signage at HWRCs is making it simpler for householders to identify the alternative disposal options for their waste and hence will make it increasingly likely that those discarding HHW may do so via a separate collection facility. Separate collection means that HHW can be treated as hazardous waste and hence treated appropriately prior to disposal at, for instance, hazardous waste landfills.

Unlike other waste types, in many countries general MSW (including codisposed HHW) sent to landfill is relatively unregulated, with no waste separation or proof of contents. Consequently, hazardous materials can be disposed of alongside nonhazardous waste, in such a way that the presence of hazardous organic contaminants can be identified in MSW landfill leachate (Fig. 17.2 [21]). As markets open up, consumers may be

exposed to a greater range of products and manufacturers are likely to produce a wider variety of merchandize to compete effectively. This could result in the utilization of a greater diversity, and amount, of chemicals, while ongoing assessments throw more and more substances into the domain of “potential hazard,” such as phthalates, monosodium glutamate, and antibacterial agents. Hence, waste streams are not only constantly growing but are also becoming more varied than at any time in the past. Although HHW represents a small fraction of total household waste, and an even smaller amount of total MSW, the range and types of hazardous substances used in households have the potential to cause problems on disposal, particularly to the aquatic environment. Because of the predominance of landfill disposal around the world, through landfill the environmental consequences of HHW disposal will be most apparent (Fig. 17.2). Alternative disposal practices, from recycling to incineration, generate waste that is ultimately landfilled.

At present, in the UK, hazardous household material (such as antifreeze, petrol and diesel, mercury in devices, paint products, herbicides, insecticides, household cleaning fluids, engine oil, cooking oil soaked rags, and gas cylinders) are not collected at the kerbside but may be deposited at one of the many county disposal sites. There are also special disposal sites for items such as asbestos, fluorescent tubes, light bulbs, fridges and freezers that contain CFCs, certain types of batteries, cathode ray tube TVs and monitors, LCD screens, computers including laptop computers, and other electrical items containing hazardous material (WEEE). There are also many private waste management companies willing to collect and dispose of such material for a fee. In the UK used batteries may be collected by retailers who sell batteries, and it is their responsibility to dispose of them. Medicine must be returned to pharmacies for disposal.

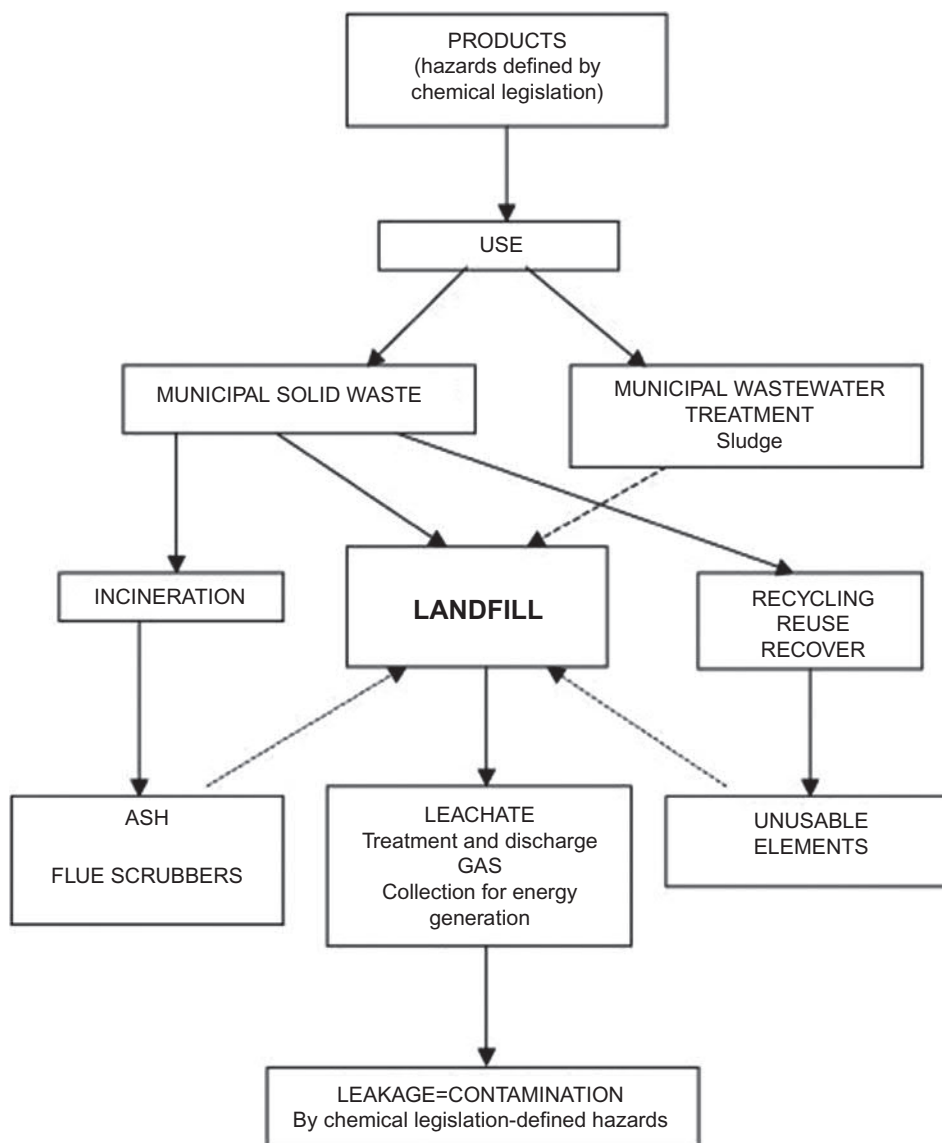


FIG. 17.2 Hazardous household waste is predominantly disposed of to landfill. Alternative means of disposal, such as to sewer, incineration, or through recycling, contribute fractions of waste to landfill [21].

Household hazardous material deposited at county waste sites in the UK is separated and the chemicals are sent to a private company where they are either recycled or incinerated; fridges and freezers are also sent to a private

company that specializes in recycling or removal and disposal of the refrigerator gases; low energy light bulbs containing mercury are sent to a private company specializing in mercury recovery and the manufacture of new

lamps. In the county of Somerset, asbestos is landfilled in a special landfill near Bridgewater and gas cylinders are either recycled or sent back to the suppliers. Again, in Somerset, batteries are sent to a private, dedicated company for recycling, separation, and disposal of valuable components.

5 ENVIRONMENTAL AND HEALTH RISKS

The level of risk posed to the environment and human health through the use and disposal of HHW is associated with the amounts of wastes produced (hazard potential) and the disposal routes adopted (probability that exposure pathways leading to a pollution event). As discussed in the preceding sections, data are scarce regarding the amount of individual waste categories and even HHW as a whole, but it is generally acknowledged that landfilling of HHW is currently the most common disposal method adopted around the world. Emissions from landfill take two forms: gaseous emissions of volatile organic compounds (VOCs) and leachate, and both have been the subject of much research as they have the potential to cause localized air quality issues and groundwater contamination [15, 22–33].

The leakage potential of a landfill is mitigated by a number of factors. Locating landfills in appropriate strata that act to attenuate releases resulting from waste disposal to land is common practice for older “dilute-and-disperse” landfills as well as newer engineered landfills. In modern landfills, the use of barrier material, most usually a combination of geomembrane and clay liner, at the base of the landfill slows the migration of landfill leachate to the surrounding environment while leachate collection systems transfer leachate for recirculation within the landfill or for removal from the landfill for treatment prior to release. Capping of filled waste cells (used to separate the landfill site into

manageable sections) and closed sites, combined with daily covering of disposed waste, reduce rainwater ingress and limit leachate production. A cap barrier restricts gaseous emissions, particularly if a gas collection system is incorporated. Failure of any of the control measures or insufficient treatment of collected emissions may result in the release of a cocktail of chemicals, as reported by Schwarzbauer and coworkers [29]. For older landfills (largely completed before the 1990s), the implementation of measures to prevent release to the environment is less well defined with the result that aquifer contamination has been far more common alongside high levels of localized VOCs [28]. As water extraction from surface water and groundwater sources increases, the knowledge of the geochemistry of leachate plumes becomes an important consideration.

Leachate is inherently variable due to the heterogeneity of waste composition, water infiltration rate and amount, residual refuse moisture content plus factors relating to the landfill: design, operation, management, and age [15]. Leachate components result from the types of waste disposed and the processes occurring within the landfill. The presence of inorganic compounds including heavy metals and hazardous organic contaminants, such as halogenated aliphatic compounds, aromatic hydrocarbons, phenolic compounds, and pesticides, in MSW landfill leachate is a direct indicator of the disposal of hazardous wastes in MSW [22, 23, 34]. However, care must be taken with MSW leachate analyses that reveal the presence of harmful substances due to the codisposal of industrial liquid wastes and manufacturing wastes with MSW, a practice no longer permitted in the EU. The consequences of HHW disposal are therefore obscured in many leachate studies. Where it is possible to differentiate waste sources, leachate composition has the potential to act as a useful tool in HHW risk evaluation.

A simulation of the landfill environment, using the LandSim modeling software, demonstrated

that contaminants linked to HHW may enter the environment around the landfill as a consequence of the degradation of the engineered barrier system (EBS) and cessation of leachate management [35]. A worst-case scenario found that certain inorganic substances (arsenic, chromium, cadmium, and mercury) might exceed groundwater-reporting thresholds several decades or even centuries after waste was first deposited and after management measures have long ceased. The concentrations of most contaminants, however, were lower than most statutory guidelines/regulations and demonstrated significant levels of attenuation within the unsaturated zone beneath the landfill and above the aquifer. These risks, though small, are likely to be reduced further in the future with improved management of HHW.

Other disposal routes also have environmental and health risks with which they are associated. Energy-from-waste (EfW) incineration provides a more rapid, less space intensive disposal alternative to landfill with the benefit of energy (heat and power) production. The production of dioxins from chlorinated organic hydrocarbons is one major disadvantage [36], but the use of flue scrubbing agents helps reduce emissions to the atmosphere. The disposal of resulting scrubbers and ash is another problem. EfW incineration is the preferred means of disposal for a number of European countries including the Netherlands, Denmark, and Germany where emissions from incinerators are heavily regulated by EU legislation. Disposal to sewer rather than as solid waste may also be used as a means of discarding HHW, particularly household cleaners/detergents (and during use), pharmaceuticals, pesticides, paint-related products, and so on. Sewage treatment processes can remove some of these hazardous substances but some substances may affect the sewage treatment process and/or pass into receiving waters unchanged. Reported risks associated with sewer disposal include localized pollution events

(e.g., heavy metal, solvents, etc.), leakage to groundwater from septic tanks, release of endocrine-disrupting substances, antibiotic resistance, and even eutrophication arising from phosphate elevation associated with detergent use (conventionally a nonhazardous product) [37–43]. Illegal disposal of HHW may also be practiced, for example, side-of-the-road dumping or fly tipping, and this can lead to large-scale pollution events. However, it is rare and criminal charges can result from such activities. Other risks can result from events happening during collection, treatment, and storage prior to disposal, including accidental spills, toxic/flamable gas release, explosion, or fire [44]. Risks are greatest at these times to waste handlers and other workers such as firefighters.

6 WASTE LEGISLATION

Change is a constant feature of the UK waste policy. Since the publication in 2000 of the Waste Strategy for England and Wales, significant changes, largely driven by EU waste laws, have been made to how waste is produced and disposed of in the UK. Building on the gains of the 2000 policy and the subsequent 2007 Waste Strategy for England, Defra published in 2013 a new Waste Management Plan for England. Wales, Scotland, and Northern Ireland also have equivalent waste strategies. However, there is little new legislation, since 2011, relating to HHW apart from the note that items such as the following cannot be put in the general waste bin for kerbside collection and must be separately collected under Hazardous Waste consignment procedures:

- Fluorescent tubes
- Cathode ray tube televisions and monitors
- LCD screens and laptops
- CFC containing fridges and freezers

- Certain types of batteries
- Mineral oil or oil soaked rags and cleaners

In the EU, the Landfill Directive 1999/31/EC is having a considerable effect on the composition of the waste being disposed of to landfill as Europe attempts to reduce the amount of waste landfilled and improves recycling rates to improve resource efficiency [45]. Diversion of putrescible waste (garden and kitchen waste) to composting facilities and separation at source of paper/card, glass, and metal cans will result in a different composition of household waste. A proportional increase of HHW in MSW may then result which may lead to changes in the composition of leachate. It is currently unclear whether these changes will be beneficial or disadvantageous to HHW codisposal to MSW landfills. Diversion of HHW from MSW landfill would, however, reduce the likelihood of HHW-associated environmental contamination scenarios from occurring. The disposal of certain substances, not only asbestos but also some waste types that can be considered part of HHW such as car tires, WEEE, and end-of-life vehicles, is specifically controlled by legislation. These are exceptions and despite inclusion as a hazardous waste in the appropriate lists [5], HHW is generally excluded from the requirements of hazardous waste legislation in the EU unless it is separately collected at, for instance, HWRCs [46]. This exclusion from the Hazardous Waste Directive 91/689/EC, therefore, permits householders to avoid being classed as hazardous waste producers but allows hazardous waste codisposal with MSW.

HHW in the United States is exempt from the definition of hazardous waste provided in Subtitle C (hazardous waste management) of the Resource Conservation and Recovery Act (RCRA) but is still subject to Subtitle D (solid waste management) regulations with other municipal wastes [47, 48]. However, if HHW is

mixed with small quantity or large generator waste, full Subtitle C regulations may be applicable. European and US regulation of HHW is therefore very similar. In Australia, the inappropriate disposal of HHW to sewer, storm water drain, or landfill is a breach of a person's general environmental duty as described in the Environment Protection Act 1993 [49]. However, separate collection is not mandatory and a variety of schemes are used to encourage householders to remove HHW from general MSW, many of which include extended producer responsibility and voluntary product stewardship schemes. The Canadian province of Manitoba has developed draft regulations along similar lines, aimed at introducing compulsory product stewardship of 11 categories forming HHW. Most Canadian provinces have adopted a nonregulated, voluntary approach to the management of HHW [50], an approach that is adopted to some extent elsewhere around the world. In South Africa and Japan, for example, most HHW disposal guidelines are restricted to advice offered to householders [51].

7 MANAGEMENT

Current management of HHW is extremely variable within, as well as between, countries, often with neighboring regions operating very different strategies for the collection and disposal of HHW. In Europe, the United States, and other countries, the central governing bodies have deferred the control and disposal of HHW to local authorities. Most local authorities have Web sites focusing on HHW (see references to HHW from Indiana (USA) [52], New Mexico (USA) [53], Somerset County (UK) [54], Durban (South Africa) [51], Tarrant County (USA) [55], Lewisville (USA) [56]). South Africa, like many developing countries, is yet to establish mechanisms for special HHW collections. Many of the

local authorities do offer collection advice and some even offer to assist in the collection of household hazardous material. However, the lack of consistency in treatment of HHW can result in confusion among householders and increase the possibility of a failure to adapt to changes in waste management.

In many areas of the United States, local community programs have been implemented to inform and educate the public of HHW. This has resulted in a well-publicized collection of programs that can take the form of one day a month or week collection at a central convenient site. Here the HHW is identified, packaged, and then transported to a permitted hazardous waste facility. In spite of the apparent popularity of the program, only a small proportion of the public is currently involved and a more sustained effort is required to raise awareness of the services offered [57, 58]. The local community programs also place a stress on informing the public of the hazardous nature of many of the materials used within the home, promoting not only waste reduction, but also product replacement with less potentially hazardous substances, for example, use of lemon juice as a household cleaner [39]. Educational programs have also sought to change householders' behavior regarding the use and disposal of potentially hazardous substances [59].

Changes in the management of all municipal wastes will also have consequences for the future collection and disposal of HHW. Source segregation of MSW is increasing as many recyclable or reusable materials are diverted from disposal to encourage the sustainable use of natural resources, for example, paper, plastics, and metals. As a consequence, the proportion of HHW in the residual waste stream may also increase, resulting in potentially more concentrated hazardous waste being disposed of to landfill. However, increased provision of separate collection for many HHW streams will lead to a diversion from MSW codisposal and so may prevent a proportional increase of HHW in

MSW. Separate collection of HHW will also require that the wastes are treated as hazardous wastes rather than as a MSW stream. Based on current practice in Europe, United States, and elsewhere, it is likely that, despite the absence of any legal obligation to do so, waste disposal authorities will seek to enlarge and encourage the separate collection of HHW and diversion from MSW codisposal. The cost of improving HHW collection services must, however, be considered alongside the pattern of declining hazardous content of consumer products, principally through the implementation of legislation including the EU's REACH Regulation (EC) No. 1907/2006, Restriction of the Use of Certain Hazardous Substances Directive 2002/95/EC and Batteries Directive 91/157/EEC [60–62]. For instance, flat screen televisions will eventually make CRT recycling facilities redundant although many household chemicals, principally cleaners, become more benign. HHW management strategy needs further clarification at national levels to ensure that practical and cost-effective measures for collection and disposal are adopted with the communication of clear and unambiguous instructions to householders. Such a strategy may consider the points provided in Box 17.2 and communication to householders may consider the checklist provided in Box 17.3.

8 FINAL NOTE RELATING TO UK ISSUES

There have been no UK directives on HHW since 2011 but historical directives relating to HHW for the UK can be found at Ref. [63]. A Circular Economy package from the EU will come into force in July 2018 and that will require separate collection of household hazardous waste from 2025. This can be found at Ref. [64]. Furthermore, a new UK Government Resource Strategy is expected for the UK at the end of 2018 and might include a mention of HHW.

FOR REFERENCE PURPOSES ONLY

BOX 17.2

STRATEGY FOR HHW MANAGEMENT

HHW management may take the form of the following points:

- The public must be involved and must appreciate the problems related to HHW.
- Publicizing local disposal and collection schemes and guidelines, providing adequate explanation for reasoning behind the schemes adopted.
- There should be both national and local initiatives, for example, flyers, Web sites, public notices, news stories, and so on, for publicizing the management of HHW, giving the same unambiguous message.
- Regular door-to-door collections to include householders without their own transport.
- Easily accessible internet and telephone help lines should be available.
- Access to clearly signposted household waste recycling centers.
- Take back schemes at retail centers for WEEE, CFC-containing household appliances, and so on.
- Voluntary schemes/legislation to encourage/ensure manufacturers disclose the contents of all potentially hazardous products and use appropriate labeling schemes.
- Ensure householders and waste handlers are educated of the dangers inherent in collecting and sorting of HHW.

BOX 17.3

GOOD HOUSEKEEPING CHECKLIST FOR THE PURCHASE, USE, STORAGE, AND DISPOSAL OF HHW

- Always buy just enough for the job in hand and try not to keep/store hazardous chemicals—use up, recycle, or dispose in the proper manner.
- Seek a less hazardous alternative if possible.
- Use hazardous chemicals in well-ventilated areas using the appropriate protective clothing/equipment.
- Always follow the manufacturers' instructions for use, storage, and disposal as provided on the product label, the instruction manual, or safety data sheet.
- If you have to store a chemical, ensure that it is out of the way of children and pets, is properly sealed, and labeled.
- Do not store flammable liquids or gas canisters in the house, storing instead in well-ventilated sheds outside.
- Always know how and/or where to dispose of your hazardous chemicals—including medicines, engine oil, WEEE, pesticides, and so on. Most householders in Europe and North America have access to a household waste recycling center, many of which cater for the disposal of HHW.
- Discard any unlabeled products, particularly if not stored in original containers.
- Never dispose of a hazardous chemical by burning, mixing with other chemicals, pouring/burying in gardens, disposing to storm water drains or directly to surface water bodies, flushing to septic tanks, or pouring to sewer drains, unless explicitly permitted in manufacturers' instructions.
- Do not add HHW to the normal household refuse collection if an alternative collection facility (e.g., HWRC) is available.
- Contact your local environmental health, solid waste management, or public works department for information on correct disposal of HHW and collection/disposal facilities.

9 CONCLUSIONS

HHW is a small proportion of the municipal waste stream, but the potential risks to the environment and health are disproportionate to its size. Although estimates of the amount of HHW vary from region to region and across national boundaries, it generally comprises 1%–4% of MSW. Estimates vary partly due to different use patterns around the world and partly to poor definition of what is considered as HHW with some definitions including bulky items such as waste electrical and electronic equipment and CFC-containing household appliances. Internationally, most HHW is codisposed with MSW to municipal waste landfills. Codisposal of potentially hazardous wastes can lead to an increase in hazard status; not only are these substances potentially dangerous to the environment and health, but they can also induce changes in other waste streams by reacting directly with the waste or by altering the redox environment (particularly acids, alkalis, and solvents). Certain substances may also adversely affect the EBS in landfills and the scrubbers used in incineration flues, increasing likelihood of environmental release. Landfill simulations, based on current MSW disposal patterns, reveal the risk to the environment from leakage of potentially hazardous materials from landfills to be small but existent. There is a growing tendency for waste disposal authorities to make provision for the separate collection of many items of HHW. The increased cost of separate HHW collection and disposal must be considered alongside the new environmental and health risks posed by changes to disposal practice and the general trend of reduced hazardous content of most consumer goods.

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Reusing Nonhazardous Industrial Waste Across Business Clusters

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1 INTRODUCTION

Nonhazardous industrial waste (NHIW) is distinct from both municipal solid waste (MSW), the mixed refuse from homes and businesses, and hazardous waste, materials that are regulated owing to their toxicity and related public health concerns. Both definitions and regulations of NHIW vary greatly from jurisdiction to jurisdiction and country to country. The US Environmental Protection Agency reports that “industrial nonhazardous waste” or “industrial solid waste” [1]:

consists primarily of manufacturing process wastes from sectors such as organic and inorganic

chemicals, primary iron and steel, plastics and resin manufacturing, stone, clay, glass and concrete, pulp and paper, and food and kindred products, including wastewater and non-wastewater sludges and solids, and construction and demolition materials.

2 STATUS OF NHIW

The amount of NHIW is vast. Yet, quantifying NHIW generation, reuse, and disposal has been difficult and uncertain, because there are many diverse sources of waste with few means to track them. As for international trends in waste generation, *EUROSTAT—Statistics Explained* presents data from European countries for 2014 that break down into several industrial

sectors [2]. The waste statistics reported by Eurostat for selected countries include waste generated from these categories: agriculture, forestry, and fishing; mining and quarrying; manufacturing; the energy sector; water and wastewater; construction; services; and household waste as shown in Fig. 18.1. With all of these categories included, household waste is only about 8% of the total (Fig. 18.1). Agriculture and mining wastes, however, may or may not be counted as NHIW as some systems aggregate them separately. When comparing NHIW estimates across geographies much care is needed to see the extent to which reported categories are consistent.

The mid-1980s was the last time that a comprehensive estimate was made in the United States. At that time, the amount of NHIW,

including water and wastewater components, totaled 7×10^9 t (seven billion metric tons) when compared with only 2×10^8 t of MSW. Of the 7×10^9 t, the pulp and paper industry comprised the largest portion, approximately 30%, followed by primary iron and steel (17%), electric power generation waste (14%), and inorganic chemicals (12%) with these four industries representing more than 70% of NHIW [3]. Disposal ranged from on-site pits, ponds, and lagoons to special impoundments, to landfills located on- or off-site. A recent study corrects these 1980's numbers, showing how they overestimate NHIW by more than an order of magnitude by including water and wastewater—liquid wastes—in estimates of solid waste [4]. Using mass balance and other methodologies, Krones now estimates that the solid waste

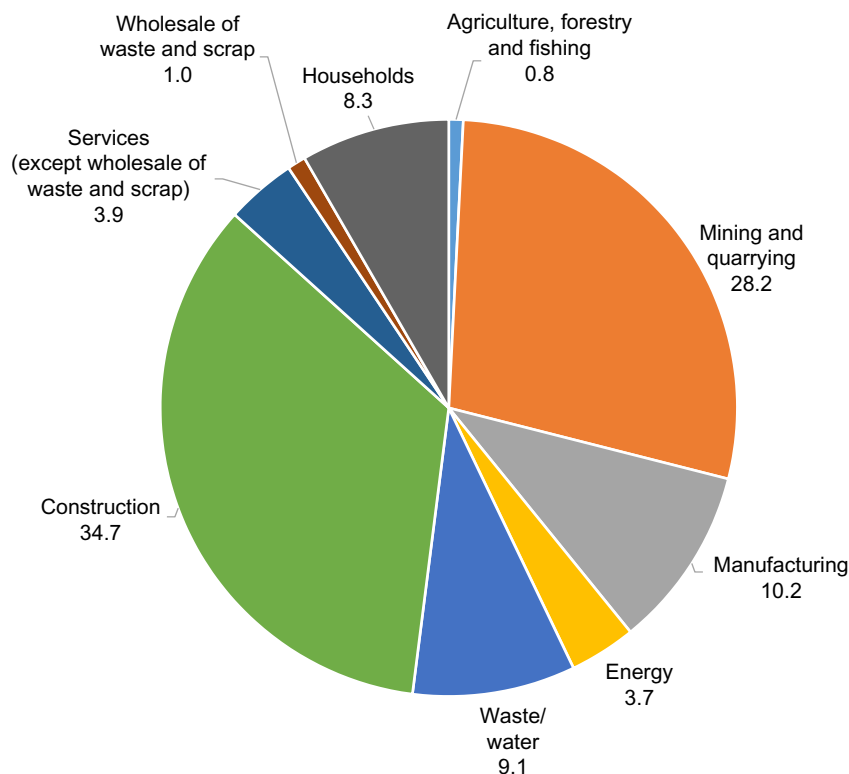


FIG. 18.1 Total waste generation and its composition in selected countries [2] (OECD 2008) (unit: million metric tons).

portion of U.S. NHIW drops from 7×10^9 t of NHIW to a more modest $200\text{--}300 \times 10^6$ t per year depending on the list of nonhazardous industrial waste. To develop a better sense of quantities, it is instructive to examine one state in the United States, Pennsylvania, that has extensive regulation of NHIW, more than any other jurisdiction identified. Since 1994, the State of Pennsylvania has tracked 110 material categories of what they term “residual waste” on a biennial basis from all companies that discard at least 12 t per year (13 short tons per year) of NHIW. Not only does the state report where the waste is generated, but it also reports each waste destination across 13 classifications, some of which represent disposal, such as landfills and impoundments, and others that represent recovery, such as composting or recycling. From these data, we can see both broad and specific patterns. With respect to the overall trend, total NHIW declined from 635×10^6 t (700 million short tons) in 1994 to 476×10^6 t in 2004 when wastewater is included. For solid residuals only, total generation declined from 34×10^6 t (37 million short tons) in 1994 to 18×10^6 t in 2004 to 14×10^6 t in 2014 [5]. The 18×10^6 t of solid residuals still exceeds the total MSW generated in the state, recorded as 8.7×10^6 t in 2016. The residual waste data also permit spatial mapping of specific wastes by quantity and geography.

Although waste and the bartering of by-products go back to ancient times, as industry has expanded, waste, too, has increased greatly especially since World War II. The sheer quantities of NHIW raise the question of how best to manage it. The first defense is cleaner production: generating less waste by increasing industrial efficiency and effectiveness. A broad range of companies now produce “annual sustainability reports” detailing the amount of waste reduced in particular categories, year to year. For wastes that continue to be generated, many large volume industrial streams are amenable to separate handling for products such as foundry sand, coal ash, and paper mill sludge. Indeed, some of these

streams are heavily reused. In 2010, for example, 42% of all coal combustion by-products were beneficially reused in the United States, 91% were beneficially reused in 15 countries in the European Union, and 96% in Japan [6].

3 INDUSTRIAL SYMBIOSIS

A critical strategy discussed in this chapter is reuse of NHIW materials within industrial clusters such that one company’s waste can become another company’s raw material. There is a long history of these types of reuse networks especially within single-industry-dominated clusters such as pulp and paper operations, integrated petroleum complexes, and sugarcane complexes [7]. Less attention has been paid to multiple-industry clusters where a great deal of waste can be exchanged safely among companies in quite different industries with significant environmental benefits. The idea of creating economic and environmental benefits through interfirm waste exchange has taken on the name “industrial symbiosis.” The expression “symbiosis” builds on the notion of biological symbiotic relationships in nature in which otherwise unrelated species exchange materials, energy, or information in a mutually beneficial manner—the specific type of symbiosis known as mutualism [8].

The model of industrial symbiosis in a multiple-industry cluster was first fully realized in the small city of Kalundborg, Denmark. The primary partners in Kalundborg, an oil refinery, power station, gypsum board facility, pharmaceutical plant, and the City of Kalundborg, share water, steam, and electricity, and also exchange a variety of wastes that become feedstocks in other processes. High levels of environmental and economic efficiency have been achieved and have led to many other less-tangible benefits involving personnel, equipment, and information sharing.

Specifically, industrial symbiosis is part of a new field called industrial ecology. Industrial

ecology is principally concerned with the flow of materials and energy through systems at different scales, from products to factories and up to national and global levels. Industrial symbiosis focuses on these flows through networks of businesses and other organizations in local and regional economies as a means of approaching ecologically sustainable industrial development. Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity [8]. Benefits achieved by industrial symbiosis have been shown to reduce environmental impacts, increase material use efficiencies and ultimately, present a more sustainable means of industrial production.

4 THE PATTERN OF INDUSTRIAL SYMBIOSIS

In this chapter, approximately 200 instances of interfirm exchanges of industrial waste were collected at 13 industrial clusters in different

parts of the world. As shown in Fig. 18.2, the geographical location of these sites spans Europe (Kalundborg, Styria, Forth Valley, and Humberside), North America (Guayama, Campbell, and Sarnia-Lambton), Asia (Kawasaki, TEDA, Guigang and Ulsan), and Oceania (Kwinana and Gladstone). The selection of the sample sites is determined by data availability: waste recovery in these sites has been studied in depth and is sufficiently documented to serve as a basis for tracking material flows among waste generators and users. To present the maximum number of waste reuse possibilities encountered for each exchange, all waste reuse cases are compiled, whether they are currently operating, proposed, or discontinued.

There is great variability among these clusters as presented in Table 18.1. Kwinana, for example, is a 120-km² mineral processing region in Western Australia [22]. In Japan, Kawasaki's industrial cluster has featured waste reuse among steel, cement, chemical, and paper industries as a part of the national "Eco-town" Program that has helped cities reuse secondary materials [16]. In China, the Tianjin Economic-Technological Development Area spans 45 km² and has thousands of companies. The Guitang



FIG. 18.2 Thirteen industrial sites selected in this study to analyze industrial waste reuse.

TABLE 18.1 Descriptions of 13 Industrial Clusters Worldwide Chosen for Review

Location (Country)	Main Industries	Number of Firms and Linkages ^a	Base Year	Reference
Kalundborg (Denmark)	Coal-fired power station, oil refinery, pharmaceutical/biotech industry, wallboard plant, cement, soil remediation, farms	1219	2008	[9, 10]
Styria (Austria)	Paper, saw mills, cement, construction materials, plastic, stone and ceramic, wastewater treatment, power plant	1938	1994	[11]
Forth Valley (UK)	Coal-fired, biomass, combined heat and power generation, cement, oil refinery, plastic, chemical, fertilizer industry, wastewater and sludge treatment	1410	2004	[12]
Humberside (UK)	Oil refinery, chemical, food, cement, furniture, steel, wastewater treatment, combined heat and power generation	1622	2004	[12, 13]
Guayama (US)	Chemical refining, coal-fired power station, wastewater treatment, aggregate, pharmaceuticals	65	2005	[14]
Campbell (US)	Coal-fired power station, cement, oil refining, water supply	1111	2006	[15]
Sarnia-Lambton (Canada)	Chemicals, fertilizer, polystyrene, rubber, wallboard, wastewater treatment, and hydropower station	74	1997	[12]
Kawasaki (Japan)	Steel, stainless steel, cement, chemical, paper waste, wastewater treatment	715	2009	[16]
TEDA (China)	Construction materials, glass, paper, pharmaceuticals, chemicals, food, electric/electrical equipment, tires, metal smelting, automobiles, rubber, wood, furniture, waste industry, cogeneration plant, water supply, wastewater	6860	2008	[17, 18]
Guigang (China)	Sugar, alcohol, cement, fertilizer, and paper industry	1011	2004	[19, 20]
Ulsan (South Korea)	Chemicals, oil refining, petrochemicals, textiles, metal processing, paper, water supply, wastewater treatment	1210	2004	[21]
Kwinana (Australia)	Alumina, nickel and oil refining, iron and titanium oxide, cement, chemicals, fertilizer, coal- and gas-fired power generation, water supply and treatment	3271	~2008	[22, 23]
Gladstone (Australia)	Alumina refining, aluminum smelting, cement, coal-fired power generation, sewage treatment	65	2005	[22]

^a When visualizing a web of waste exchanges as a network, a firm participating in a waste exchange represents a node in the network. One linkage is defined as a single instance of waste reuse between a generator and a user.

Group is a sugar-refining operation that uses its fiber by-products from sugarcane for paper manufacture, its organic by-products for molasses, alcohol, and other products [19, 20]. In the United States, both Guayama and Campbell have fewer than 12 actors and are anchored by coal-fired power plants that reuse wastewater and provide steam for other industrial operations [14, 15]. Similar exchanges also compose part of the cluster in Kalundborg, Denmark [24].

Based on information from academic journals and reports, we analyzed industries and industrial sectors involved in waste reuse, either as generators or as users, and catalogued the types

of industrial wastes that are exchanged. Nineteen industrial sectors, from the letter “A” to the letter “S,” are listed in Table 18.2 based on “The North American Industry Classification System” (NAICS) codes.

Numerous industrial waste materials were identified at the 13 industrial cluster sites and then grouped into 10 categories: chemical waste, metallic waste, ash, organic waste, sludge, paper and wood waste, nonmetallic waste, waste plastics and rubber, waste oil, and others (Table 18.3). Among a total of 199 industrial waste exchanges across companies, the top five waste categories in terms of the number of

TABLE 18.2 The Classification of Industries

	NAICS Code	Description
A	11	Agriculture, forestry, fishing, and hunting
B	21	Mining, quarrying, and oil and gas extraction
C	2211	Energy utilities (electric power generation, transmission, and distribution)
D	2213	Water utilities (water, sewage, and other systems)
E	23	Construction
F	311	Food manufacturing
G	313/314	Textile mills and textile product mills
H	321	Wood product manufacturing
I	322	Paper manufacturing
J	324	Petroleum and coal product manufacturing
K	325	Chemical manufacturing
L	326	Plastic and rubber product manufacturing
M	327	Nonmetallic mineral product manufacturing
N	331	Primary metal manufacturing
O	334/335	Computer and electronic/electrical equipment manufacturing
P	336	Transportation equipment manufacturing
Q	337	Furniture and related product manufacturing
R	562	Waste industries (waste collection, treatment/disposal, remediation, and other management services)
S	-	Other industries

TABLE 18.3 Summary of Waste Linkages by Industrial Waste Category

Waste Category	Material Description	Number of Observations	Industries that Generate This Waste	Industries that Use This Waste
Chemical waste	Spent solvents, residual acids/alkali, sulfur, industrial gases (CO ₂ , H ₂), activated carbon, spent catalyst	54	C, D, F, I, J, K, N, O, R	B, C, D, F, I, J, K, L, M, N, O, R
Metallic waste	Metal scraps (iron, steel, stainless steel, copper, lead, zinc), slag (blast furnace, steel, lead), solder materials, bauxite residue, spent lead acid batteries	28	I, N, O, P, R	D, K, M, N, R
Ash	Fly ash, bottom ash, mixed ash, burnt residue	26	C, I, R	A, B, E, K, M, R, S
Organic waste	Food waste, biomass, fertilizer, other organic waste	23	A, F, K, N, R, S	A, C, F, I, K, M, R, S
Sludge	Sewage sludge, refinery sludge, paper sludge, fiber muds, filter cakes	19	D, F, I, J, M, N, P, R	A, B, C, D, K, M, R
Paper and wood waste	Cardboard, mixed paper, wood dust, chips, trimmings	15	H, I, M, Q, R, S	A, H, I, M, S
Nonmetallic waste	Synthetic gypsum, construction and concrete waste, glass scrap, coal mine overburden, lime kiln dust, silica fume	14	B, C, K, M, O, R	E, M, N
Waste plastics and rubber	Polystyrene, waste plastics, off-spec plastics, rubber scrap	7	F, I, L, R	J, L, M, N, R, S
Waste oil	Used oil from chemical processes, edible oil from food manufacturing	7	F, K, R	J, K, M
Others	Textile waste, fine materials, biogas, excess gas	6	D, G, I, J, R	J, M

linkages occur in these sectors: chemical waste, metallic waste, ash, organic waste, and sludge. These are the waste materials that have been reused most frequently and, generally, where there is likely to be more recognition, knowledge, technology, and experience in reusing these materials.

Understanding how actors reuse different waste materials is critical to planning and facilitating industrial waste reuse linkages. Industrial waste reuse can occur within a facility, but the opportunity is largely limited. In this analysis, most waste reuse occurs across industries and industrial sectors. Interindustry reuse

can happen in at least two different patterns: one pattern of reuse is more concentrated in a single industrial sector whereas the other pattern is more distributed across diverse industries. As shown in [Fig. 18.3](#), the largest supplier and user of metallic waste is the primary metal manufacturing industry, although five different industries generate and five industries reuse the metallic waste. In contrast, sludge is more dispersed, as it is generated from eight industrial sectors and reused by seven different sectors. One implication of the degree of dispersion across sectors is the opportunity provided for reuse within and around multiple industry

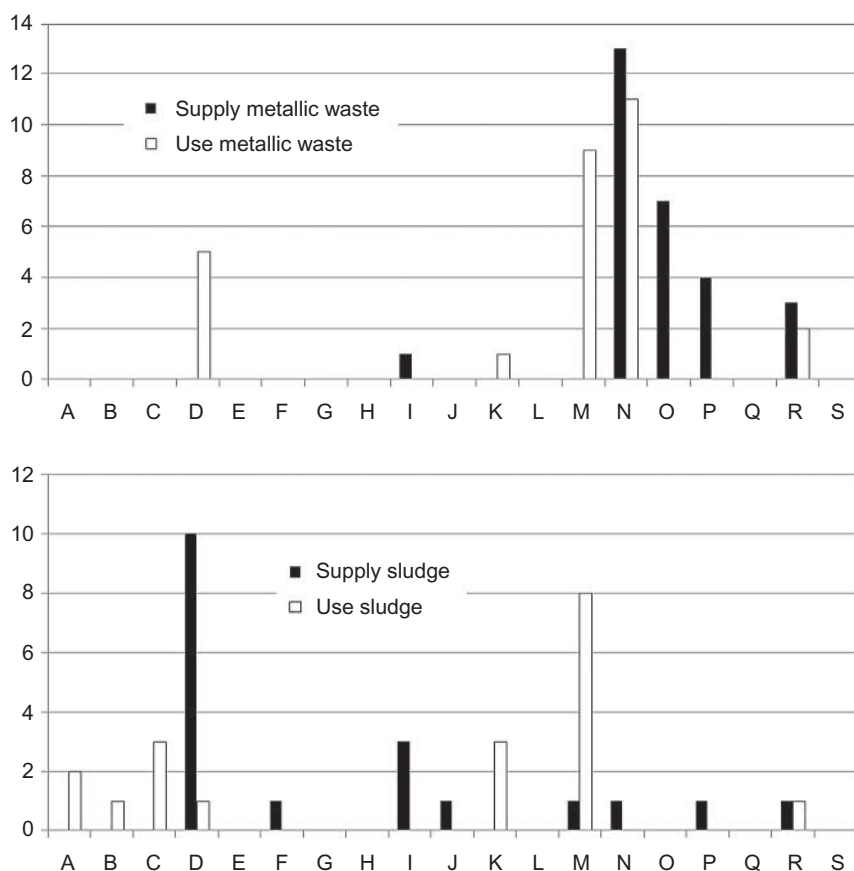


FIG. 18.3 The number of linkages for supply and reuse of waste in different industrial sectors: for metallic waste (*upper*) and for sludge (*lower*).

clusters that foster cooperation among the participants in the cluster. By offering more market channels across industries, there is likely to be less dependence on any one industry should that industry become unavailable as a reuse channel.

Industrial sectors vary in their potential either to accept or reuse waste. For example, companies in the nonmetallic mineral manufacturing sector (Industry “M”), including cement/concrete producers, lime/gypsum manufacturers, and glass and clay products manufacturers, accept waste materials from 59 other industries, but send their waste to only

five other industries (Fig. 18.4). Companies in this industrial sector primarily act as waste users and have a high capability to incorporate waste materials in their production. However, energy utilities (C) and food manufacturers (F) supply more waste materials than they receive. In the case of chemical manufacturing (K) and primary metal manufacturing (N), companies supply and use a similar quantity of waste materials in aggregate as most reuse happens within a single industrial sector.

Industries exchange not only solid waste materials (by-products) but also residual heat and secondary effluent. Often, power plants

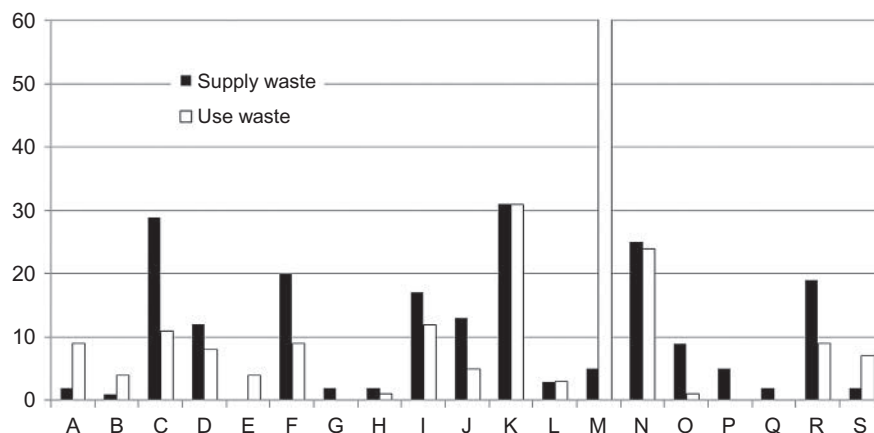


FIG. 18.4 The number of linkages for supplying waste (black bars) or using waste (white bars) observed in 13 industrial clusters across different industrial sectors from A to S.

and public wastewater treatment works provide energy, residual steam, and treated wastewater to industries nearby, a practice known as “utility sharing.” Fig. 18.5 shows that in addition to the 199 instances of solid material reuse, there are 82 utility sharing linkages observed in these industrial clusters. While energy utilities (C) and water utilities (D) dominate in supplying energy and water, petroleum and coal product manufacturing (J), chemical manufacturing

(K), and primary metal manufacturing (N) also provide some utilities as resources to other industries.

It is not the intent of this analysis to suggest that all industrial wastes could or should be reused. Many wastes pose numerous risks to human health and the environment and the first task of any program is safety. Neither can we presume, however, that many common practices today such as storing waste in piles or

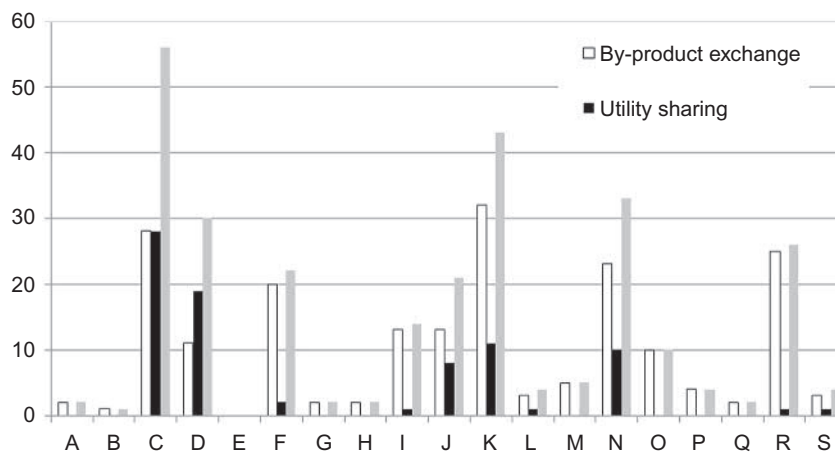


FIG. 18.5 The number of linkages for supplying by-products, utilities, and total industrial symbiosis linkages observed in 13 industrial sites across different industrial sectors from A to S.

impoundments is protective or useful. The enormous flood of coal ash escaping from a compromised impoundment in Tennessee in 2008 ended up covering 1.2 km² (300 acres) of land with 4.1×10^6 m³ (1.1 billion gallons) of coal ash flowing into the tributaries of the Tennessee River [25]. By the logic of symbiosis, it is far preferable to find safe, beneficial uses for that coal ash in the first instance. In this way of thinking, the products of the 13 industrial clusters discussed in this chapter need not be considered wastes, but should be thought of as secondary materials that could find economic and environmentally sound reuse opportunities.

Some argue that the solution to the NHIW problem is to regulate it much more closely, or, at a minimum, to increase information flows about it. Routine collection and distribution of data on the type and amount of NHIW that is available, along with clear standards for NHIW management including legal liability issues, would greatly facilitate reuse [26]. Interested jurisdictions could experiment in a systematic way with different incentives and requirements to achieve decreases in generation and disposal and increases in beneficial reuse. Perhaps most important would be the establishment of more uniform definition and categorization of NHIW across broader geographies. This would help with compositional analysis, enable improved metrics, and clarify available market opportunities.

In this chapter, we have examined industrial waste exchange networks in business clusters around the globe, discussed what kinds of industrial by-products and utility resources have been reused, determined how much or how often each waste reuse stream has been observed in different places, and also identified the industry sectors that generate and reuse them. Still, we have not dealt with the question of how waste reuse becomes organized. Some reuse networks, particularly in Asian regions

including Kawasaki, TEDA, and Ulsan in this study, are primarily planned from the top-down as a way of conserving resources and increasing efficiency. In contrast, many exchanges have been self-organized by companies as discussed in Kalundborg, Campbell, and Styria, through bilateral discussion, communication, and negotiation across industries [27]. Some networks have been facilitated by third parties including Forth Valley and Humberside in this study previously organized by dedicated entities such as the National Industrial Symbiosis Program of the United Kingdom.

A business rationale for symbiotic activity is that by acting together, proximate firms can find collective economic and environmental benefits that are greater than the sum of the individual benefits each would realize if it acted alone [28]. Specifically, firms benefit from avoiding disposal or substituting input materials at a lower total cost and may also be driven by a long-term interest in supply security. A less visible attribute of industrial symbiosis lies in the necessary condition of interfirm cooperation: industries that recognize the possibility that the whole can be greater than the sum of its parts, find an approach that extends beyond their own boundaries in ways that can be good for business and often good for the environment at the same time. The 13 industrial areas described here only capture a tiny percent of the symbiotic activity involving industrial waste that is already occurring in the field. When NHIW can be used in the ways cited in these examples, however, there is the double benefit of landfill avoidance and reuse that contributes to the productive economy. By learning about and understanding these phenomena, we can facilitate and expand the structures that enable such linkages to occur in service to a more efficient and sustainable industrial system.

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Current and Emerging Construction Waste Management Status, Trends and Approaches

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1 INTRODUCTION

The built environment consumes more natural resources than necessary and therefore generates a large amount of waste. A study by the World Resource Institute of material flows in a number of industrialized countries showed that one half to three quarters of the annual material input to these societies was returned to the environment as waste within one year [1]. Failure to consider the wider implications of economic development has led to a global environmental crisis driven by wasteful material resources. This situation triggered attempts to develop international, national, regional, and local material resource efficiency and construction and demolition waste prevention and minimization programs. The chapter examines the concept of construction waste and definitions; assesses construction and demolition (CDW) waste quantification and source evaluation; and appraises current and emerging construction waste management and minimization approaches, tools, methodologies, and technologies.

2 CONCEPT AND DEFINITIONS

Although the ideal of construction waste (CW) reduction is well acknowledged and generally accepted, it is proving difficult to implement. Traditionally, wastes have been viewed by construction stakeholders as inevitable by-products. As a result, managing on-site waste was often addressed within a legislative and health and safety context. Consequently, the perception that waste is unavoidable in construction activities disallows strategic considerations, engagement, and implementation attempts to manage construction waste at project level. There is anecdotal evidence that the overordering culture endemic across the construction sector is the result of on-site productivity issues. This has been attributed to the fact that the cost of materials excess is less than that of labor. On the

other hand, it has been widely argued that frequent design variations during the construction stage result in unsuitable or excess materials. Moving the construction industry toward a more sustainable future requires fundamental changes to current design, material procurement, and construction waste management.

Emerging sustainable thinking is redefining the concept of waste from a “by-product” of processes to missed opportunities to cut costs and improve performance. Koskela [2] went further to argue that waste adds costs but does not add value. Similarly, Formoso et al. [3] classified waste as “unavoidable,” for which the costs to reduce it are higher than the economy produced, and “avoidable,” when the necessary investment to manage the produced waste is higher than the costs to prevent or reduce it. Therefore the concept of waste should be looked at in terms of activities that increase costs directly or indirectly but do not add value to the project.

There is no generally accepted definition of waste. A common definition of waste was issued by the European Union (EU) Waste Framework Directive (WFD): “any substance or object which the holder discards or intends or is required to discard” [4]. This definition has been in use in its current wording for over three decades and applies to all waste irrespective of whether or not it is destined for disposal or recovery operations. The European Council made several revisions to the WFD, from its initial publication in 1975 to the latest amendments in October 2008 that came into force in March 2011. The revised WFD sets the basic concepts and definitions related to waste management, such as definitions of “waste,” “recycling,” and “recovery.” Significantly, the definition of “waste” has been clarified in the revised WFD through specific articles that formally introduce the concepts of “by-products” and “end-of-waste.” The introduction of a definition of by-products in WFD Article 5 formally recognizes the circumstances in which materials may fall outside the definition of waste. This change is intended to recognize that many

“by-products” are reused before entering the waste stream. It describes when “waste” ceases to be “waste” and becomes a secondary raw material (so-called end-of-waste criteria) and how to distinguish between waste and by-products. The revised WFD places greater emphasis on waste prevention. As such, the waste hierarchy (prevention, preparing for reuse, recycling, recovery, and disposal) is placed at the heart of EU waste management policies (Fig. 19.1). The WFD enabled Member States (MS) in the EU to adopt their own national definitions of waste.

For the scope of this chapter, the following definitions are adopted:

- “Construction waste” (CW) is a material or product which needs “to be transported elsewhere from the construction site or used on the site itself other than the intended specific purpose of the project due to damage, excess or non-use or which cannot be used due to non-compliance with the specifications, or which is a by-product of the construction process” [5].
- “Design waste” is the waste arising from construction sites owing directly or indirectly to the design process [6].
- “Waste minimization” is the reduction of waste at source (i.e., designing out waste) by understanding its root causes and reengineering current processes and practices to alleviate its generation [6].
- “Waste management” is the process involved in dealing with waste once it has arisen, including site planning, transportation, storage, material handling, on-site operation, segregation, reuse and recycling, and final disposal [6].

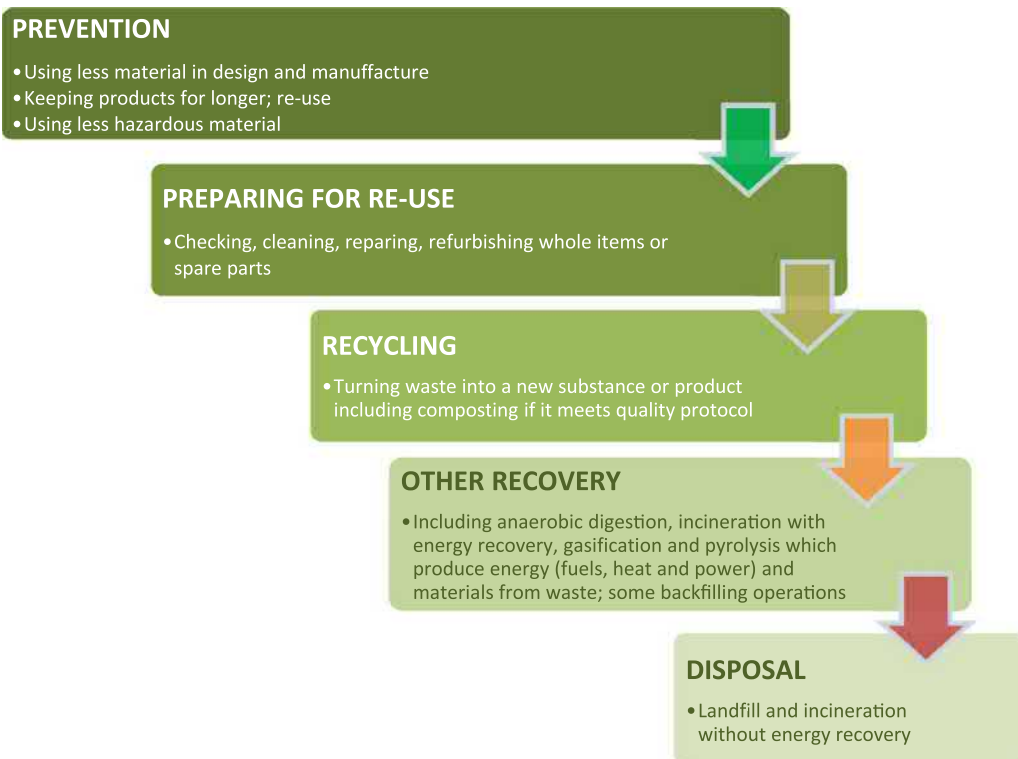


FIG. 19.1 The EU waste hierarchy.

3 CONTEXT

The construction sector is the highest producer of waste if compared with other economic activities worldwide, accounting for 35% of the total waste generation in the European Union (EU) [7], which equates to four times more than the total household waste produced, and 30%–40% in China reaching one billion tons of CDW in 2013 [7, 8]. It is estimated that the construction and demolition activities generated in excess of 850 million tonnes of physical waste in the EU and over 530 million tons (Mt) in the United States in 2014 [9].

The amount of generated CDW has been routinely considered as an indicator for comparing waste management performance across different countries. However, CDW generation at a national level is influenced by several factors, namely, gross domestic product (GDP), population, and CDW-related regulatory measures. For example, Fig. 19.2 shows the relationship between CDW generation in 2014 and GDP per capita in USA, China, and the EU. Results indicate that CDW generation per GDP is significantly higher in China if compared with the EU and USA. Indeed,

the CDW generation versus GDP ratio is around 8.58 and 3.68 Mt/GDP per capita in the EU and USA, respectively, and 27.78 CDW/GDP per capita in China.

Within the EU, the bulk of CDW generation in 2014 is attributed to mineral wastes, excluding excavated soils and dredging spoils are not considered, the different waste categories generated for each MS in the EU. Fig. 19.3 shows CDW mineral waste streams in the EU, which include

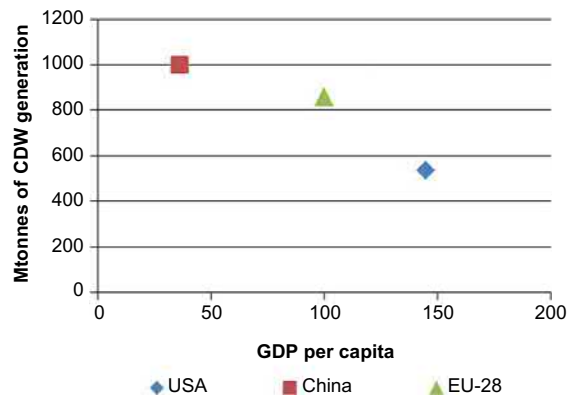


FIG. 19.2 Amount of CDW generated considering the GDP per capita in 2014.

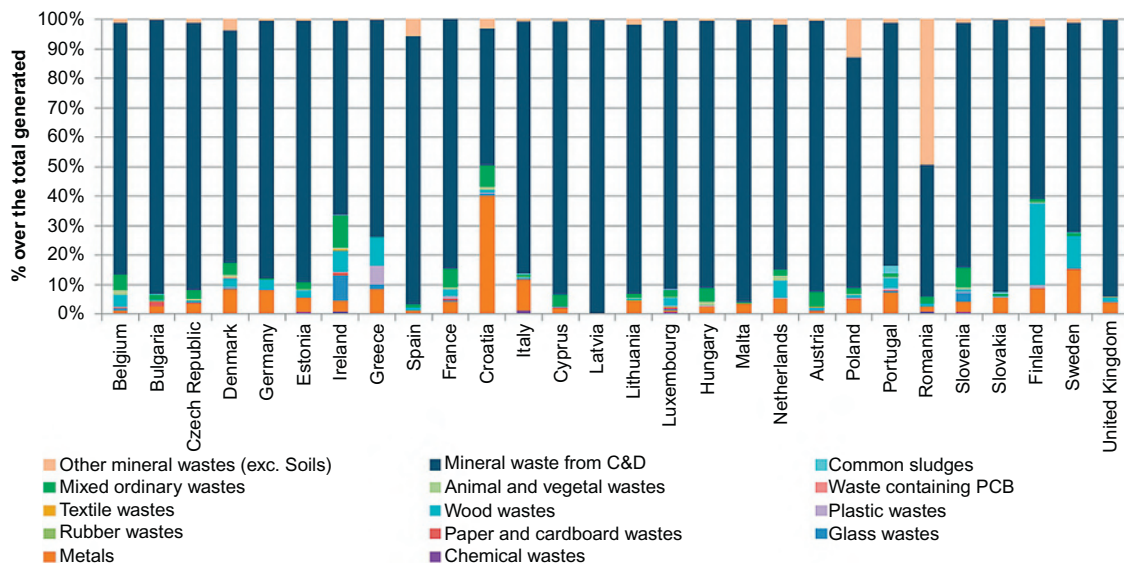


FIG. 19.3 Percentage of each waste stream generated in each Member State during 2014 (Data from Eurostat was used).

concrete, bricks & ceramics, gypsum, wood, and asphalt. Similar CDW mineral categories were generated in the United States, including 65% of bulk aggregate (primarily concrete) and 14% of reclaimed asphalt pavement [10].

In terms of CDW reuse and recycling rates, China reused and recovered around 5% of CDW, while the EU and the USA reached higher recovery rates, around 79% and 70%, respectively. Despite two-third of MS in the EU have already reached the 70% CDW recovery target set in the EU Waste Framework Directive (WFD) by 2020, there are still other EU countries which need to take further measures to improve their recovery rates (Fig. 19.4). It is interesting to note that Ireland, Malta, and Czech Republic achieved the EU WFD recovery rate target, but only if backfilling is considered. Therefore backfilling will be a determinant factor for some MS to meet the 70% CDW recovery target by 2020.

The significant differences on CDW management among the EU MS can be due to several reasons such as poor data sources and collection; no existence of national regulations dealing specifically with CDW; low landfill taxes or bans;

small number or inadequate distribution of recycling facilities; the cost of primary raw materials; and the lack of confidence in recycled materials, avoiding the existence of a market for secondary raw materials.

Considering this situation, the European Commission is encouraging the uptake of the circular economy by boosting CDW recovery and management. The EU Action Plan for the Circular Economy [11] establishes general measures to be implemented throughout the whole cycle: from design, production, and consumption to waste management and the market for secondary raw materials. The CDW-related actions considered by the EU Action Plan for the Circular Economy aim to:

- ensure improved recovery of valuable resources and adequate waste management in the construction and demolition sector, as well as facilitate assessing the environmental performance of buildings;
- develop predemolition guidelines to boost high-value recycling in the sector as well as voluntary recycling protocols aimed to

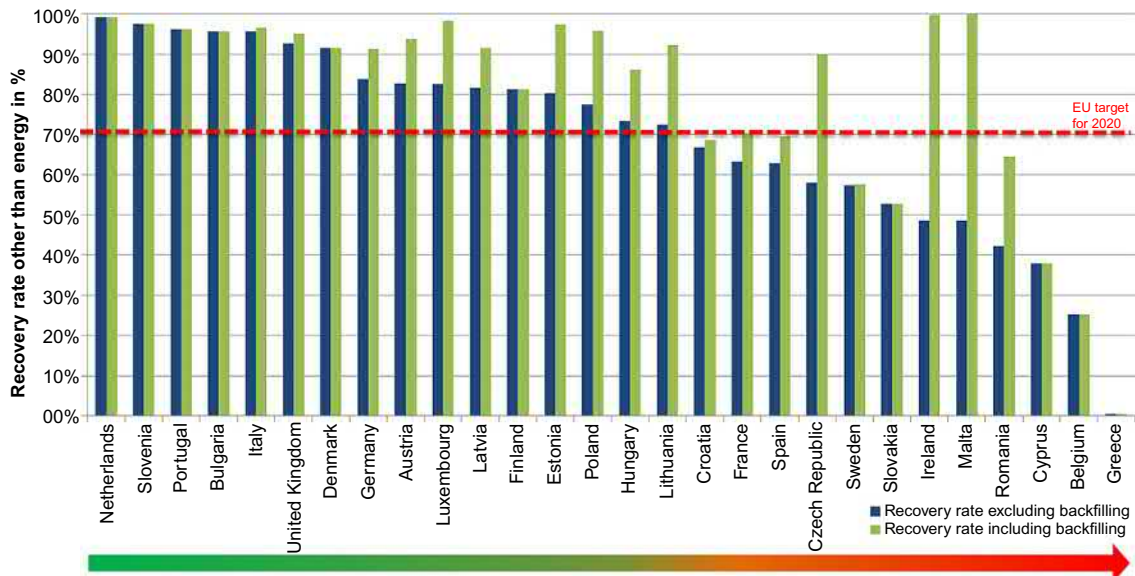


FIG. 19.4 Recovery rates of mineral waste from construction and demolition in EU during 2014 (Data from Eurostat was used).

improve quality of and build confidence in recycled construction materials; and

- propose in the revised legislative proposal on waste to require better sorting of construction and demolition waste.

Some of these actions have already taken place. For instance, in 2016 the European Commission published the *Construction and Demolition Waste Protocol* aiming to increase confidence in CDW management and the trust in the quality of recycled building materials by means of improving waste identification, source separation and collection; improving waste logistics; improving waste processing; ensuring quality management; and developing an appropriate policy and framework [12].

In general, the above actions toward circular economy contribute to close the loop of construction product life cycles, helping to build a market for secondary materials and fostering sustainable economic growth in the construction industry.

4 CONSTRUCTION WASTE COMPOSITION AND QUANTIFICATION

It is difficult to give exact figures of CW produced in a typical construction site, but previous research works estimated that 4%–30% of the total weight of building materials delivered to a building site becomes waste due to damage, loss, and overordering [13, 14]. The streams and composition of on-site wastes are highly variable, depending on the country and the construction techniques used. Table 19.1 summarizes the results from previous studies on CW quantification.

CW can be broadly classified into three categories: waste which is: (1) not easily recycled or which present particular disposal issues, including chemicals (i.e., paint, solvents), asbestos and plaster; (2) not capable of being directly recycled in the construction industry, but may be recycled elsewhere, including timber, glass,

TABLE 19.1 Percentage of Each Waste Category From the Total Generated [15–17]

Waste Stream	Spain	United Kingdom	Italy	Norway	Portugal	United States	India	China
Soil and rocks	–	–	–	–	–	–	35.00	–
Mixed concrete & ceramic waste	85.00	33.00	84.30	67.24	82.90	72.00	65.00	–
Concrete	–	–	–	85.13	–	70.00	35.00	8–35
Ceramic	–	–	–	10.48	–	2.00	30.00	15–50
Mixed waste	–	–	–	–	–	–	–	–
Wood	11.20	27.00	–	14.58	–	7.00	2.00	1–5
Paper	–	18.00	–	–	1.20	–	–	5–20
Plastic	0.20	–	–	–	0.16	–	–	–
Gypsum	–	10.00 ^a	–	–	6.40	3.00	–	–
Metals	1.80	3.00	0.08	3.63	4.50	1.00	5.00	1–8
Asphalt	–	–	6.90	–	4.20	14.00	2.00	–
Other	1.80	11.00	8.80	14.55	–	–	1.00	10–20

^a Corresponds to dry lining waste.

paper, plastic, and oils; and (3) potentially valuable and easily reused or recycled, including inert waste such as concrete, stone masonry, bricks, tiles, asphalt, and soil. In terms of waste streams and weight, brick masonry and concrete present by far the largest potential for recycling in the building sector. This has been supported by the findings of comprehensive research conducted across the United States, the United Kingdom, Spain China, Brazil, Korea, and Hong Kong, which compared the streams and volumes of construction waste in these countries.

5 CONSTRUCTION WASTE SOURCE EVALUATION

There are a variety of different approaches to the evaluation of the main origins, sources, and causes of CW. The extant of literature reveals a number of CW generation sources, which can be broadly categorized into 11 clusters. Table 19.2 presents that construction waste is generated throughout the project from inception

to completion and the preconstruction stage has its considerable share.

It has been estimated that 33% of wasted materials is due to architects failing to design out waste [18]. However, construction waste minimization through design is complex because buildings embody a large number of materials and processes. Equally, Osmani et al. [18] reported that “waste accepted as inevitable,” “poor defined responsibilities,” and “lack of training” are major challenges facing architects to design waste reduction measures in their projects. This is made more complex when further waste is created directly or indirectly by other projects’ stakeholders, namely, clients, contractors, subcontractors, and suppliers. Nonetheless, there is a general consensus that design changes during operation activities are one of the key origins of construction waste. The main drivers for design variations during construction are lack of understanding the underlying origins and causes, design changes to meet client’s changing requirements, complex designs, lack of communication between design and construction teams, lack of design information, unforeseen

TABLE 19.2 Origins and Causes of Construction Waste [6]

Origins of Waste	Causes of Waste
Contractual	Waste client-driven/enforced Errors in contract documents Contract documents incomplete at commencement of construction
Procurement	Lack of early stakeholders’ involvement Poor communication and coordination among parties and trades Lack of allocated responsibility for decision making Incomplete or insufficient procurement documentation
Design	Design changes Design and detailing complexity Design and construction detail errors Inadequate/incoherent/incorrect specification Poor coordination and communication (late information, last minute client requirements, slow drawing revision and distribution)

Continued

TABLE 19.2 Origins and Causes of Construction Waste [6]—cont'd

Origins of Waste	Causes of Waste
On-site management and planning	Lack of on-site waste management plans Improper planning for required quantities Delays in passing information on types and sizes of materials and components to be used Lack of on-site material control Lack of supervision
Site operation	Accidents due to negligence Unused materials and products Equipment malfunction Poor craftsmanship Use of wrong materials resulting in their disposal Time pressure Poor work ethics
Transportation	Damage during transportation Difficulties for delivery vehicles accessing construction sites Insufficient protection during unloading Methods of unloading
Material ordering	Ordering errors (i.e., ordering items not in compliance with specification) Over allowances (i.e., difficulties to order small quantities) Shipping and suppliers' errors
Material storage	Inappropriate site storage space leading to damage or deterioration Improper storing methods Materials stored far away from point of application
Material handling	Materials supplied in loose form On-site transportation methods from storage to the point of application Inadequate material handling
Residual	Waste from application processes (i.e., overpreparation of mortar) Off-cuts from cutting materials to length Waste from cutting uneconomical shapes Packaging
Other	Weather Vandalism Theft

ground conditions, and long project duration [19]. The main drivers for design variations during construction are:

- last minute client requirements (resulting in rework);
- designers' inadequate experience in evaluating construction methods and the sequence of construction operation (leading to detailing errors that require alteration or demolition of completed works);
- increasing design complexity (producing off-cuts);
- lack of design information (leading to assumption offers by contractors and subcontractors, which result in overordering of materials);
- unforeseen ground conditions (the risk of the uncertain nature of ground conditions is often accepted that waste may occur on modifying the design as required rather than

undertaking expensive preliminary investigations to confirm the conditions resulting in soil waste); and

- long project durations (allowing the design to be modified to suit changes in the market, research, or legislation).

Construction procurement systems-related waste sources fall under four main themes: uncoordinated early involvement of project stakeholders, ineffective project communication and coordination, unclear allocation of responsibilities, and inconsistent procurement documentation [20].

6 CONSTRUCTION WASTE MANAGEMENT AND MINIMIZATION APPROACHES

Despite international governmental, industrial, and academic efforts to develop waste reduction thinking in construction, uptake globally is piecemeal. That said, an ever-increasing global research has been devoted to figure out how to curb construction waste generation.

As presented in Table 19.3, the current and ongoing research in the field of CW management and minimization can be broadly categorized into 19 clusters.

The bulk of CW research is largely guided by the “3 Rs” principle of waste (reduction, reuse, and recycling), otherwise known as the waste hierarchy. Earlier research reports, such as the studies aimed at promoting awareness in the construction industry about the benefits of waste minimization, including cost savings. The impact of legislation on on-site waste management practices resulted in a number of research studies. Furthermore, research studies were conducted to investigate attitudinal, behavioral, and incentivized approaches to improving on-site waste management.

Tools, models, and techniques have been developed to handle and better manage on-site construction waste segregation, quantify waste generation, estimate waste generation rates, audit waste, reuse waste, and collate and analyze on-site waste streams. Furthermore, different approaches to waste source evaluation were

TABLE 19.3 Current and Ongoing Research in the Field of Construction Waste Management and Minimization

Phase	CW Management Approach	Employed Method
General	1 Impact of legislation on waste management practices	Literature review; content analysis; questionnaires; interviews; case studies
	2 BIM aided CW management	Questionnaires; interviews
Design	3 CW minimization benefits	Literature review; system dynamics; questionnaires; interviews; case studies
	4 Forecasting tools	Literature review; case studies
	5 CW quantification and composition	Literature review; observations; statistical models; questionnaires; interviews; case studies; archival analysis; mass balance principles
	6 CW source evaluation	Literature review; questionnaires; interviews
	7 Procurement waste minimization	Literature review; questionnaires; interviews
	8 Design waste minimization	Literature review; questionnaires; interviews; system dynamics

Continued

TABLE 19.3 Current and Ongoing Research in the Field of Construction Waste Management and Minimization—cont'd

Phase	CW Management Approach	Employed Method
Construction	9 Waste reduction potential through modern methods of construction and off-site construction	Literature review; workshops; observations; questionnaires; interviews; case studies
	10 On-site CW sorting methods and techniques	Literature review; observations; questionnaires; interviews; case studies
	11 CW flow modeling	Literature review; Life Cycle Analysis (LCA); Material Flow Analysis (MFA); system dynamics; questionnaires; interviews; case studies
	12 On-site waste auditing and assessment tools	Literature review; software packages and online protocols
	13 On-site waste management practice improvements	Literature review; Life Cycle Analysis (LCA); system dynamics; questionnaires; interviews; case studies
	14 CW minimization standards and guides	Literature review; focus groups; workshops
	15 Attitudes toward CW minimization	Literature review; questionnaires; interviews
	16 Comparative waste management studies	Literature review; system dynamics; questionnaires; interviews; case studies; Big Data Analysis
End-of-life	17 Recycling and recovery technologies	Literature review; case studies
	18 CW reuse, recycling and recovery	Literature review; observations; laboratory experiments
	19 Postnatural disaster waste management	Literature review; case studies

developed to identify construction and design waste causes. Additionally, an increased number of studies were conducted to assess the potential impact of Modern Methods of Construction (MMC) and off-site construction techniques on waste reduction. Emerging information technologies, bar coding systems, GPS, GIS, and wide area networks (WANs) are being progressively introduced into construction waste research. At the end of the waste management research spectrum, various waste recycling “soft” decision making and marketing methodologies and “hard” laboratory technologies and resulting improved waste have been developed as a last attempt to divert construction waste from landfill. While these methods facilitate waste auditing, assessment, reuse, and recycling; they were developed to manage waste that has already been produced. As such, there is

insufficient effort and no structured approach to address waste at source and specifically design waste. That said, it is widely argued that future waste efforts should focus on designing out waste [19]. The last few years witnessed an increasing, yet, limited design waste-related research studies, including Building Information Modeling (BIM) aided waste minimization [21].

7 CONSTRUCTION WASTE MINIMIZATION AND MANAGEMENT TOOLS, METHODOLOGIES, AND TECHNOLOGIES

Several construction waste management tools, methods, and technologies are being used in the construction industry to (1) forecast and

design out waste; (2) manage on-site waste; and (3) recycle and recover end-of-life materials and products during preconstruction, construction, and demolition stages, respectively.

7.1 Preconstruction Stage: Forecasting and Designing Out Waste

At present, there are insufficient design decisions supporting tools to integrate designing out waste strategies in construction projects. However, the last few years witnessed an increasing; yet, limited design waste-related research. Indeed, social CW awareness together with the increasing waste legislation and fiscal measures developed has led to the development of an ever-increasing number of templates, guides, manuals [22] and Standards (BS 8895: Designing for material efficiency in building projects) to support designers to embed waste minimization in their projects.

In particular, Waste Management Plan templates provide automated templates to facilitate the development of waste management plans and thus calculate variables of interest such as waste output and costs. Furthermore, WRAP [22] introduced a guide containing broad guidance for architects to adopt a fivefold waste minimization strategy in their projects. The guide comprises the following five principles: design for reuse and recovery, design for off-site construction, design for material optimization, design for waste-efficient procurement, and design for deconstruction and flexibility. Although the content of WRAP designing out waste guide is a step forward to engage architects in designing out waste, the guide did not associate the proposed principles with all parameters of the design process environment, including stakeholders' coordination, communication, and roles. More importantly, the guide failed to conduct a waste diagnosis across all design stages to map out the direct and indirect design waste origins, causes and sources that are

critical in informing and implementing designing out waste principles and strategies.

Waste prediction tools estimate potential CW generation in building projects. In general, these tools are based on aggregating waste indices or ratios which are obtained by dividing the amount of CW generated (in volume or weight) by either the amount of materials purchased or per the gross floor area of the project (m^2). For this, reliable ratios for CW estimation are essential in order to plan an efficient waste management system for a construction site or a region. Methods, which were developed to estimate CW generation, vary depending on the scope of CW estimation: regional level or construction project. Studies at a regional level estimate the CW generation within an area by multiplying the construction activity by the waste generation rate determined at a project level. Most of these studies have sourced data from government statistics to estimate the construction activity of a region. Therefore data sources play a significant role in these studies as they are directly related with the accuracy of the estimations. Furthermore, case studies are usually adopted to gain knowledge on CW generation and composition. Researchers have used different techniques for data collection such as field observations, sorting and weighing on site, truckload records and surveys. Several studies analyzed CW generation rate according to several factors: building use, structural typologies, dwellings' size, or a combination of them; while others analyzed the accumulation rate of construction waste throughout the whole project duration [23].

For example, performance indicators for individual CW products have been produced from completed projects on *SMARTWaste Plan*. These performance indicators have been applied to construction output to provide an estimate of waste arising by product from new build construction and refurbishment and determine on-site waste management methods and actions for each waste type. Similarly, WRAP developed *Net Waste Tool* to help generating waste forecasts

during site operations and prioritizing waste reduction and recovery actions to input into a Site Waste Management Plan.

However, a number of recent studies used a multiple linear regression analysis, proposed a statistical model to determine the amount of waste generated by assessing the influence of design process and production system [24]. These culminated in the generation to a set of design variables related to compactness of the building, the practice of waste recycling in the construction site, the floor plan area, and the adopted construction system. That said, the latter was restricted to a very limited number of broad design variables that are specific to high-rise buildings. As such, it did not offer a comprehensive model to assess the impact of all design processes on on-site waste production for any type of building projects.

In the last few years, a limited literature suggests that Building Information Modeling (BIM) has the potential to drive out construction waste in building. It has been argued that BIM techniques can be used by architects as a platform to minimize design waste in their projects; structural engineers to reduce construction generation for structural reinforcement and demolition contractors to optimize reuse, recycling, and recovery during demolition and renovation activities. However, methods and tools that integrate informed designing out waste strategies across all project stages are absent in the literature.

7.2 Construction Stage: On-Site Construction Waste Management

The main contractors are considering environmental issues, not being limited to the current legislation, and seeking the implementation of sustainable CW management practices. Increasingly, construction companies are aware of the impact of building activities on the natural environment on the one hand, and Corporate Social Responsibility on the other. As such, they

introduced several CW management practices, including development of a site waste management plan for each project, on-site CW management training packages for their workers and subcontractors, and innovative processes aimed at minimizing waste and selecting recycled and recyclable materials. However, despite large construction companies' endeavors to reduce and better manage CW, the vast majority of small and medium enterprises in the construction industry engage significantly less in the process and their approach is predominantly reactive to legislative requirements.

Several construction waste management tools, such as site waste management plans, toolbox talks, and material bar-code systems, are being used during the construction stage. On-site waste management tools have been developed to handle and better manage on-site construction waste segregation; quantify waste generation; estimate waste generation rates; waste data analysis; audit construction waste; reuse on-site waste and collate and analyze on-site waste streams.

In particular, CW estimation and quantification tools are used to calculate the quantity of waste generated from building projects. Data collection and audit tools record the amount, type, and sources of waste generated in a building project. For example, *CALIBRE* and *ConstructClear* are tools which allow project management teams to refine on-site processes, by recording real time data on site to measure on-site efficiency and quantifying CW. *SmartStart* in the United Kingdom and *WasteSpec* in the United States are tools to facilitate on-site auditing and thus evaluate the waste management performed across all the construction sites of a company.

Furthermore, an increased number of studies were conducted to assess the potential impact of off-site construction techniques on on-site waste reduction. Emerging information technologies, bar coding systems, GPS, GIS, and wide area networks (WANs) are being progressively introduced to effectively manage on-site waste.

7.3 End-of-Life Waste Recovery, Recycling, and Circularity

In the last few years, location-based tools, which are usually GIS enabled, have been developed to provide the location of CW management services. For example, *BREMap* developed a searchable map to find the nearest facility for CW recycling facilities.

The quality of CW is directly influenced by the performance carried out in the construction and/or demolition site. For instance, one of the main difficulties for waste recovery is the collection of mixed waste (instead of on-site sorting) and the inefficient mechanical sorting of the mixed waste. Therefore the workers' attitude and training regarding CW management is essential for enhancing CW sorting and also

more efficient waste sorting technologies are needed to generate cleaner CW for recovery.

By and large, technologies used for waste recovery, recycling, and circularity encompasses three interrelated methods: source collection and separation, processing, and recovery and treatment. Fig. 19.5 shows a summary of the different technologies for CW recovery used in each stage of the process.

8 CONSTRUCTION WASTE MANAGEMENT CHALLENGES AND INCENTIVES

Despite the evidence to support the economic and business benefits of waste reduction, the construction industry has been slow to reform



FIG. 19.5 CW recycling and recovery technologies.

its practices. The literature identified a variety of constraining factors that impede the construction industry to adopt a sustainable waste minimization approach. These are largely due to the conservative aspect of the industry. It is widely established in the literature that the major construction waste minimization constraints are related to perceptions and attitudes toward waste management. The main challenges facing project stakeholders to adopt effective waste reduction strategies in their projects are:

- Lack of managerial commitment.
- Lack of industry construction waste minimization norms.
- Difficulties in changing existing practices.
- Lack of operatives experience in waste management.
- Perception that waste management systems are not cost effective.
- Waste accepted as inevitable by-product of construction.
- Unwillingness to reuse or recycle materials with little economic value.
- Extra costs to implement CW-related strategies and initiatives.
- Any savings made are unequally distributed, therefore giving little incentive for workers to participate in waste management.
- Poorly defined individual responsibilities for waste management.
- Limited waste minimization guidance.
- Time consuming devoted to sorting out and handling on-site waste, thus extending the work plan schedule.
- An increase of red tape can be found due to extra paperwork for filling control forms, inspection reports, and so on.

On the other hand, “financial rewards” and “legislation” seem to be the main incentives that could drive waste minimization in the construction industry. Although there is a consensus that legislation can be effective in maintaining the pressure in improving waste minimization, it was suggested that financial drivers at project level will have a far-reaching

impact on waste reduction practices. Waste minimization financial benefits are related to the direct costs of both waste disposal and raw material purchase. However, the true cost of waste is estimated to be around 20 times the disposal of waste. A study by a major UK contracting company revealed that that a typical construction skip costs around £1343. This figure is broken into £85 for skip hire (6.4% of cost), £163 for labor (12.1% of cost), and £1095 of cost of wasted materials (81.5% of cost). Therefore the financial cost of waste for a generic house (five skips) is around £6715, of which £5439 is attributed to the cost of discarded materials.

9 DISCUSSION AND CONCLUSIONS

The current thinking of waste minimization practices is heavily focused on the physical minimization of construction waste and identification of site waste streams. Tools, models, and techniques have been developed to help handle and better manage on-site waste generation. Although these tools facilitate auditing, assessment, and benchmarking, their waste source evaluation approach is curtailed and piecemeal, as it fails to effectively address the causative issues of waste production throughout all stages of a construction project. The challenge now is to provide a novel platform for the next generation of tools and techniques that will identify and resolve the fundamental causes and origins of construction waste. The basis for such an approach could utilize Building Information Modeling (BIM) and related technologies, in particular Virtual Prototyping, to provide a platform for “virtual” waste evaluation which reviews and assesses the severity of waste generation throughout all stages of the construction project life cycle. Although BIM design methods are not currently as fully utilized in the construction industry as in other industries, there is general recognition that BIM adoption will become more

pronounced to demonstrate not only the entire building life cycle but also assess and evaluate the environmental performance and impacts of buildings.

Construction waste minimization can be viewed as a threat requiring ever-increasing expenditure on end-of-pipe recycling tools and technologies to meet ever-increasing legislation, or as an opportunity to cut costs and improve performance. The choice should be obvious, but there is a need for a culture change. Rethinking waste management in construction requires adopting “cyclic” rather than “linear” approach to design and construction. This requires reengineering current practice to contribute to a cleaner environment through efficient and cost-effective sustainable waste minimization strategies. However, for waste minimization to be effective and self-sustaining, it is important that all stakeholders along the construction supply chain embrace a more proactive approach in dealing with waste. In recognition of the responsibility of the architectural profession, through its leading role in project management and a key player in the construction industry, architects should move beyond the concept of “eco-efficiency” through bolt-on environmental strategies and strive to adopt “eco-effective” practices by implementing a holistic approach to design out waste, which will be reinforced in tender documents and implemented during the construction stage, in addition to the capture and dissemination of lessons learnt to inform construction waste reduction baselines and benchmarking in future projects.

Achieving “zero waste” will be a breakthrough strategy for a world in an environmental crisis; however, this is a highly challenging target in construction, but involving and committing all stakeholders to reduce waste at source and developing efficient waste management strategies by reusing and recycling materials and components can take the industry closer to the “zero waste” vision, hence, moving from myth to reality.

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Thermal Pollution

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OUTLINE

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1 INTRODUCTION

Is heat a bad thing or a good thing for the environment? As Duke engineering professor, Jeff Peirce, is fond of saying, the only universally correct answer in engineering is, “It depends” [1]. From a waste management perspective, heat is both friend and foe. Indeed, the first edition of this book included separate chapters on the implications and applications of thermal energy in waste management. Thermal treatment is now included in [Chapter 31](#), in discussing ex situ destruction of hazardous wastes. When properly designed and operated, incinerators and other thermal technologies reduce municipal and industrial wastes in volume and change their physical and chemical properties to make these wastes less toxic and more easily manageable.

The purpose of this chapter is to address the problems caused by excess heat, that is, direct thermal pollution. For the waste manager, the challenge of heat is incremental. Notwithstanding a major disaster, such as an explosion at an incinerator, it is most likely the waste management approach will contribute heat to a system. The added thermal energy can lead to adverse changes in ecosystem condition, diminishing the integrity of the system (see [Chapter 8](#)). Heat is also an indirect pollutant. If not operated properly, any use of heat, including the same technologies used to treat wastes, can form very toxic chemical compounds. Most industrial processes make ample use of chemical reactions at high temperatures, which not only release excess heat to the environment, but often generate chemical pollutants.

Organisms and ecosystems survive within a range of environmental conditions. Considering the extremes in temperature on the other planets for which we have data, the earth's temperature range is quite small. The temperature tolerances of even the most adaptive earth-bound creatures are quite tight. Thus one of the key factors in public health and environmental conditions is the temperature range.

Anthropogenic, that is, human induced, activities can alter the heat balances within the environment. Like other essential factors needed to sustain life, heat is a pollutant if situations so dictate. Just as too much or too little oxygen or water stresses an organism or ecosystem, an optimal temperature range exists. This range varies among species. Thus releasing heat into an environmental system can change the habitat of one or more species so that the temperature falls outside of the optimal or survival ranges.

The added heat may also indirectly affect the environment, by altering other conditions that harm organisms, including humans; notably changes in dissolved oxygen in surface waters. Such input can occur at any environmental scale. For example, at the cellular level, a small-scale change to a portion of an aquatic system interferes with microbial metabolism. At the planetary scale, large-scale changes in global heat balances increase seasonal ambient temperatures, which can cause or worsen human health and ecological problems. For example, the higher ambient temperatures are associated with increased incidences of heat stress, and these same temperature increases along with other indirect climate changes can adversely impact ecosystems and human populations. Recent studies predict if climate change leads to more frequent episodes of temperature increases at the local scale, i.e., the heat island effect in many cities, this would likely result in higher incidences of cardiovascular and respiratory diseases and related deaths [2, 3]. Studies have also shown that the effects will not be evenly distributed. In fact, some locations are predicted to experience local cooling extremes, which could also affect

human health and ecological conditions. The changes are also likely to harm the poorer populations [4].

As mentioned, changes in the heat budget can adversely affect the environment indirectly. For example, adding heat to an ecosystem potentially affects sensitive species, from microbes to plants to animals, by sea-level rise, increased intensity of extreme weather events, and altering micrometeorological patterns, but also by habitat loss and by changing natural cycles, for example, nutrient cycle changes that modify rates and size of algal blooms and disease outbreaks [5]. These changes affect the most sensitive species first, but the effects are compounded given the food-prey relationships. Loss of or diminished food species harms the next trophic level if a substitute is not available, and even the substitute were available this could alter other species dependent on this as their principal or exclusive food source. Thus even small changes in heat can induce substantial changes in biological organization and trophic state [6, 7].

Thermal pollutants can affect the environment in every phase and environmental media. Heat may be a water pollutant if its addition directly or indirectly harms the biota living in surface waters. The raised temperatures in water, for example, can alter the biodiversity of an ecosystem in two ways. The increased temperature may not be tolerable for aquatic biota and/or the increased temperature increases microbial growth, which in turn decreases dissolved oxygen, makes metals more bioavailable, or in other ways increases the harm from nutrients and toxins.

2 CUMULATIVE EFFECTS OF THERMAL POLLUTION

Direct heating of substrates, for example, water, air, and soil, can cause environmental harm. Microclimatological changes can occur due to the release of heated plumes from combustion facilities and vehicles. Even soil that

receives added heat can be polluted if it changes the habitat (e.g., changes to freeze-thaw cycles, seasonal variations, and selectivity) of certain soil biota (e.g., bacteria, plant root systems and fauna like earthworms, burrowing and nesting animals). Such pollutants need to be treated, such as by cooling towers before heated water reaches surface water and other sensitive habitat.

Heat can initiate cumulative environmental impacts, such as the heat exchange and changing conditions of receiving water bodies [8]. In fact, the value of a fishable stream can be directly related to water temperature since it defines the dissolved oxygen content, which is a limiting factor of the type of fish communities that can be supported by a water body (see [Tables 20.1 and 20.2](#)). A trout stream is a highly valued resource that is adversely impacted if normal temperatures increase. Rougher, less valued fish (e.g., carp and catfish) can live at much lower ambient water body temperatures than can salmon, trout, and other cold-water fish populations. Thus net increase in heat may directly stress the game fish population. That is, fish species vary in their ability to tolerate higher temperatures, meaning that the less tolerant, higher value fish will be inordinately threatened.

The threat may not be completely explained as heat stress is also related to an increase in temperature [9]. Much can be explained by the concomitant decrease in the stream's dissolved oxygen (DO) concentrations (see [Figs. 20.1 and 20.2](#)), which deems the water body hostile to the fish. Even if the adult fish can survive at the reduced DO levels, their reproductive capacities diminish; or if the reproduction is not adversely affected, survival rates of juvenile fish decline [8].

Chemical reactions are temperature dependent. As an example, chemical substances toxic to organisms become more soluble and bioavailable as temperature increases. Thus aquatic organisms' exposure to harmful substances increases. For example, greater concentrations

TABLE 20.1 Relationship Between Water Temperature and Maximum Dissolved Oxygen (DO) Concentration in Water (at 1 atm)

Temperature (°C)	Dissolved Oxygen (mgL ⁻¹)	Temperature (°C)	Dissolved Oxygen (mgL ⁻¹)
0	14.60	23	8.56
1	14.19	24	8.40
2	13.81	25	8.24
3	13.44	26	8.09
4	13.09	27	7.95
5	12.75	28	7.81
6	12.43	29	7.67
7	12.12	30	7.54
8	11.83	31	7.41
9	11.55	32	7.28
10	11.27	33	7.16
11	11.01	34	7.16
12	10.76	35	6.93
13	10.52	36	6.82
14	10.29	37	6.71
15	10.07	38	6.61
16	9.85	39	6.51
17	9.65	40	6.41
18	9.45	41	6.41
19	9.26	42	6.22
20	9.07	43	6.13
21	8.90	44	6.04
22	8.72	45	5.95

Source of data: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015; E. Dohner, A. Markowitz, M. Barbour, J. Simpson, J. Byrne, G. Dates, 5.2. Monitoring and assessing water quality, in: *Volunteer Stream Monitoring: A Methods Manual* 1997.

of mercury and other toxic metals will occur with elevated temperatures. The lower DO concentrations will lead to a reduced environment where the metals and compounds could form

TABLE 20.2 General Temperature Tolerances of Aquatic Organisms

Organism	Taxonomy	Range in Temperature Tolerance (°C)	Minimum Dissolved Oxygen (mg L ⁻¹)
Trout	<i>Salma</i> , <i>Oncorhynchus</i> , and <i>Salvelinus</i> spp.	5–20	6.5
Smallmouth bass	<i>Micopterus dolomieu</i>	5–28	6.5
Caddisfly larvae	<i>Brachycentrus</i> spp.	10–25	4.0
Mayfly larvae	<i>Ephemerella invaria</i>	10–25	4.0
Stonefly larvae	<i>Pteronarcys</i> spp.	10–25	4.0
catfish	Order Siluriformes	20–25	2.5
Carp	<i>Cyprinus</i> spp.	10–25	2.0
Water boatmen	<i>Notonecta</i> spp.	10–25	2.0
Mosquito larvae	Family Culicidae	10–25	1.0

Source of data: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015; V. Corporation, *Computer 19: Dissolved Oxygen in Water*, 2018. Available from: http://www2.vernier.com/sample_labs/BWV-19-COMP-dissolved_oxygen.pdf.

sulfides and other compounds that can be toxic to the fish. Thus the cascade of effects, beginning with the change in temperature, followed by a decrease in DO and increasing metal concentrations, can be further exacerbated by the synergistic impact of the combining the hypoxic water and reduced metal compounds that harm to the stream's ecosystems [10] (see Fig. 20.3).

2.1 Abiotic-Biotic Relationships

Biotic factors change during a heat-initiated effect. Abiotic mechanisms, for example, hydrolysis and redox, combine with and influence

biotic response, for example, photosynthesis and respiration. Notably, the growth and metabolism of the bacteria results in even more rapidly decreasing DO levels. Algae both consume DO for metabolism and produce DO by photosynthesis. The increase in temperature increases their aqueous solubility and the decrease in DO is accompanied by redox changes, for example, formation of reduced metal species, such as metal sulfides. This is also being mediated by the bacteria. The decrease in DO changes the redox potential of the water and sediment, initiating or increasing the rate of the reduction of metals. However, the opposite is true in the more oxidized regions, that is, where the metals are forming oxides. The increase in the metal compounds combined with the reduced DO, exacerbated by the increased temperatures, can act synergistically to make the conditions toxic for higher animals, for example, a fish kill [11]. This is an example of how an outcome can become a new stressor.

The first-order abiotic effect, that is, increased temperature, results in an increased microbial population. However, the growth and metabolism of the bacteria results in decreasing the DO levels, but the growth of the algae both consume DO for metabolism and produce DO by photosynthesis. Meanwhile a combined abiotic and biotic response occurs with the metals. The increase in temperature increases their aqueous solubility and the decrease in DO is accompanied by redox changes, for example, formation of reduced metal species, such as metal sulfides. This is also being mediated by the bacteria, some of which will begin reducing the metals as the oxygen levels drop (reduced conditions in the water and sediment). However, the opposite is true in the more oxidized regions, that is, the metals are forming oxides. The increase in the metal compounds combined with the reduced DO, combined with the increased temperatures can act synergistically to make the conditions toxic for higher animals (see Fig. 20.4). As Fig. 20.5 demonstrates, the movement of mass and energy downstream,

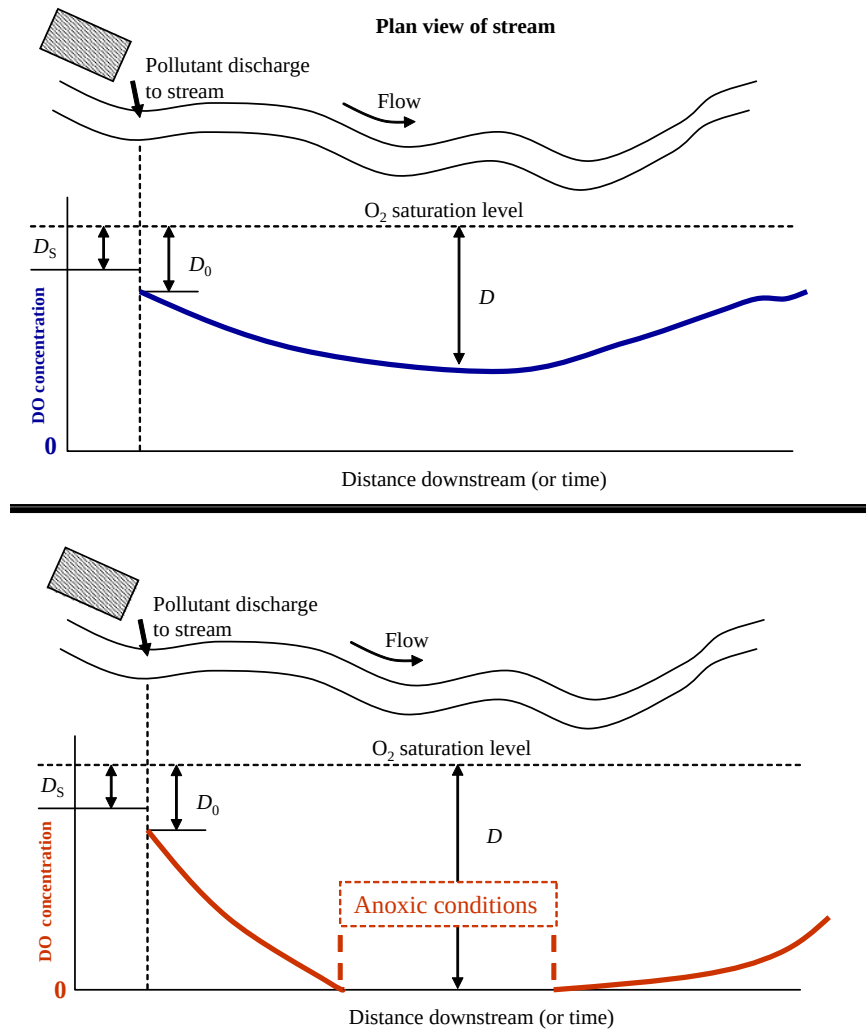


FIG. 20.1 Dissolved oxygen (DO) deficit downstream from a heated effluent. The increased temperature can result in an increase in microbial kinetics, as well as more rapid abiotic chemical reactions, both consuming DO. The concentration of dissolved oxygen in the top curve remains above 0, so although the DO decreases, the overall system DO recovers. The bottom sags where dissolved oxygen falls to 0, and anoxic conditions result and continue until the DO concentrations begin to increase. D_s is the background oxygen deficit before the pollutants enter the stream. D_0 is the oxygen deficit after the pollutant is mixed. D is the deficit for contaminant A which may be measured at any point downstream. The deficit is overcome more slowly in the lower curve (smaller slope) because the reoxygenation is dampened by the higher temperatures and changes to microbial system, which means the system has become more vulnerable to another insult, for example, another downstream source could cause the system to return to anoxic conditions.

both figuratively and literally, results in an adverse aquatic outcome, for example, a fish kill [11]. Predicting the likelihood of a fish kill can be quite complicated, with many factors that either

mitigate or exacerbate the outcome. This is a classic depiction of Bayesian thinking, that is, prior events must update predicted outcomes, for example, posterior probabilities [12].

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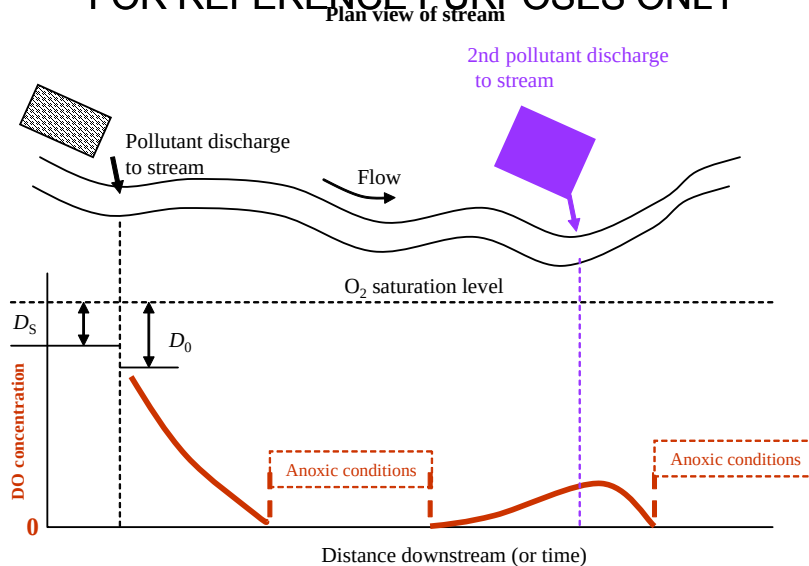


FIG. 20.2 Cumulative effect of a second heat source on dissolved oxygen concentrations, rendering the overall aquatic system more vulnerable. The rate of reoxygenation is suppressed by second heat source, causing anoxic conditions to return.

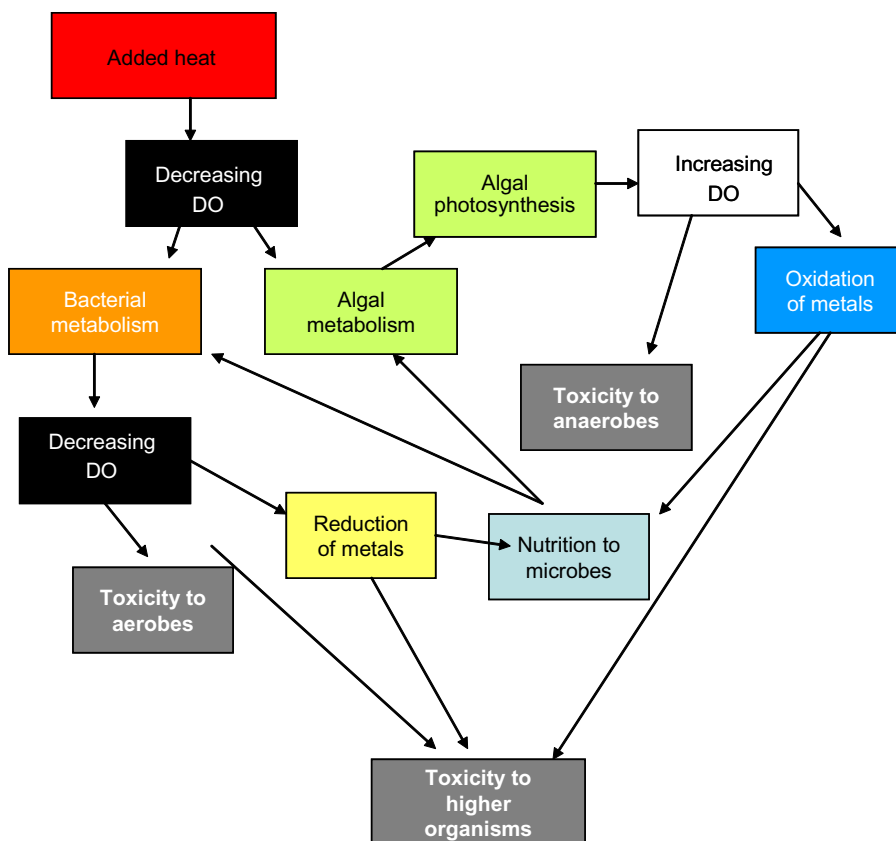


FIG. 20.3 Cascade and network of adverse effects in the real world usually result from a combination of conditions. In this example, the added heat results in an abiotic response, that is, decreased dissolved oxygen (DO) concentrations in the water, which leads to other abiotic and biotic responses. Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015.

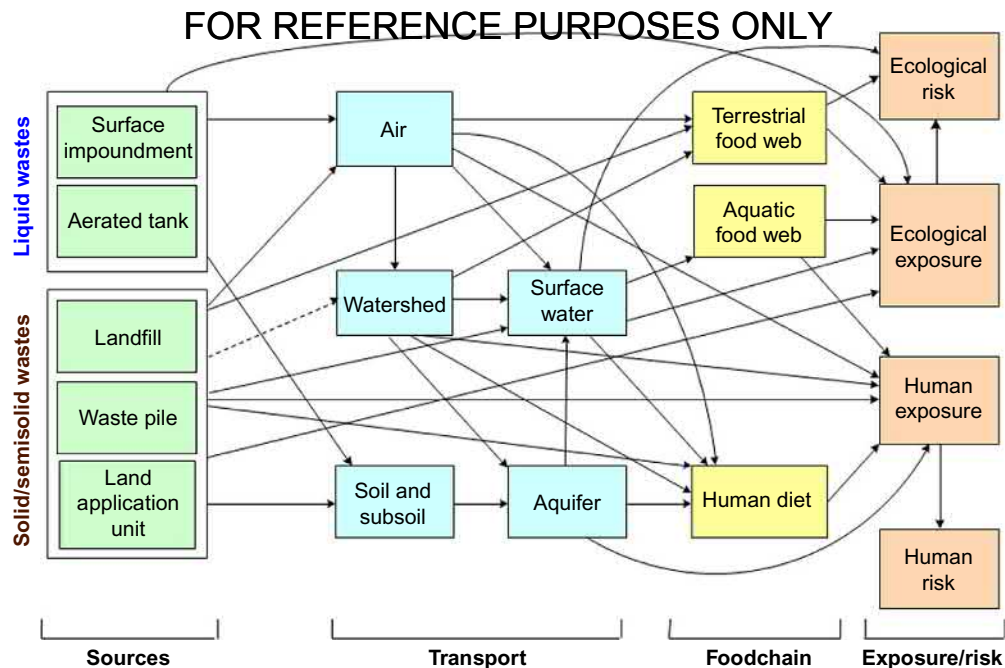


FIG. 20.4 Environmental transport pathways can be affected by net heat gain. Compounds (nutrients, contaminants), microbes and energy (e.g., heat) follow the path through the environment indicated by arrows. The residence time within any of the boxes is affected by conditions, including temperature. *Adapted from D.A. Vallero, K.H. Reckhow, A.D. Gronewold, Application of multimedia models for human and ecological exposure analysis, International Conference on Environmental Epidemiology and Exposure, Durham, NC, International Society of Exposure Analysis, 2007.*

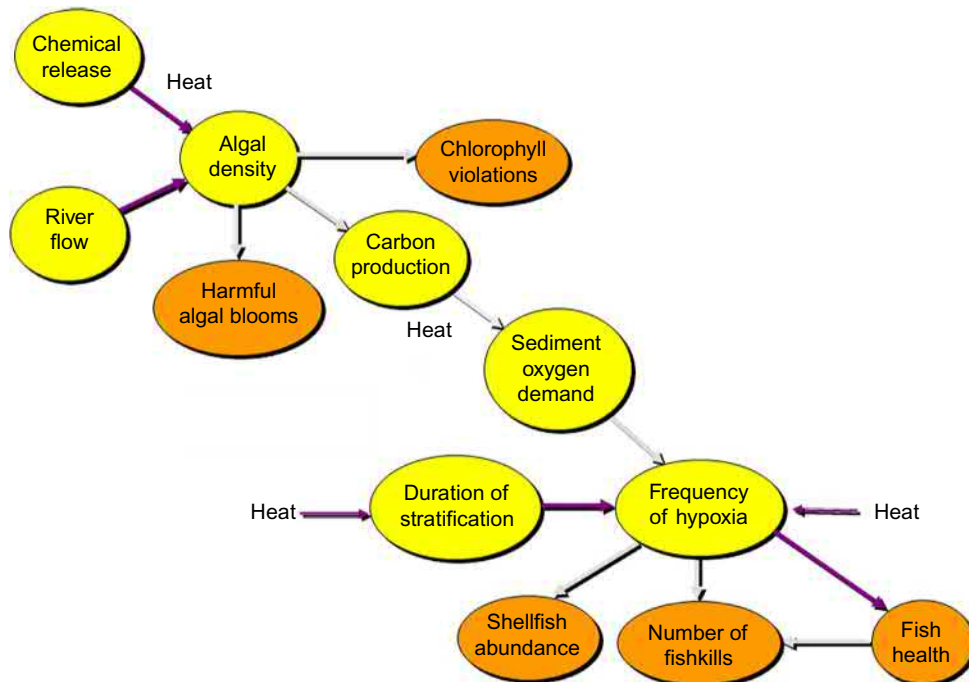


FIG. 20.5 Flow of events and conditions leading to fish kills indicate some of the points where added heat can exacerbate the likelihood of a fish kill or other adverse environmental events. *Source: D.A. Vallero, K.H. Reckhow, A.D. Gronewold, Application of multimedia models for human and ecological exposure analysis, International Conference on Environmental Epidemiology and Exposure, Durham, NC, International Society of Exposure Analysis, 2007.*

The first law of thermodynamics requires that releasing heated water in any amount to a water body, even at the permitted level, would increase the overall temperature of the receiving stream. Power plants in the United States release heated water to rivers and streams (see Fig. 20.6). The first edition of this book erroneously stated that once-through cooling, that is, passing water through turbines and then directly discharging the water to adjacent streams, was no longer allowed in U.S. waters (see Fig. 20.6A). Indeed, the practice continues. Other cooling systems continue to replace this practice [13], for example, closed-cycle cooling systems, dry cooling systems, and discharging to cooling lakes. Thus power plant water systems became more closed, both from a fluid dynamics and thermodynamic perspective (Fig. 20.6B). However, there are still numerous power generating facilities that employ once-through cooling. In 2012 over 400 plants were cooling turbines with this water, which are contributing a sufficient amount of added heat to adversely affect aquatic life [14].

3 THERMO-CHEMICAL POLLUTION

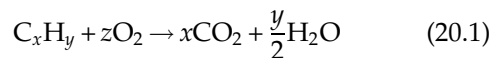
Heating processes have generated almost every class of pollutants discussed in in this book. Indirect thermal pollution usually involves changing the physical, chemical, and biological integrity of a system. From a thermodynamic perspective, the environment is subdivided into a network of control volumes. One important type of thermal pollution is indirect thermo-chemical pollution that results from changes in the heat budgets within these control volumes. For example, the secondary gases generated in thermal technologies discussed in Chapters 24 and 31 can cause or exacerbate the generation of chemical air pollutants. These, in turn, may be released to the atmosphere and eventually cause harm when deposited in the

ecosystem or in human populations who breathe the air. These effects can be mediated by control technologies, such as secondary combustion chamber for more complete combustion of incinerator gases or wet scrubbers for their removal, as well as electrostatic precipitators and fabric filters to remove particulate matter (see Chapter 24). Better still, by designing systems that require less heat or wherein heat is managed properly, the thermal pollutants can be prevented from being generated in the first place.

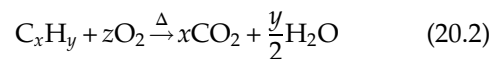
3.1 Thermo-Chemical Formation of Carbon Compounds

Pollutants form from thermal processes, no matter if the heat is intentionally generated. Every National Ambient Air Quality Standard (NAAQS) health-based pollutant, that is, the so-called criteria air pollutants are formed by thermal chemical reactions. The bulk of gas-phase criteria pollutants emitted, that is, carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), ozone (O₃), are almost exclusively formed in thermal reactions. Particulate matter (PM) is also produced thermally, among other processes, such as physical erosion. Some of the lead (Pb) emissions are also generated thermally, although this is declined since Pb has been progressively removed from motor vehicle fuels.

Many of the toxic air pollutants, for example, many volatile organic compounds (VOCs), are formed thermally in internal combustion engines, fires, and industrial processes. For VOCs, the general stoichiometry is:



If the reactants in the chemical reaction are heated, the Greek symbol delta (Δ) is often shown above the arrow. Thus the combustion reaction would be:



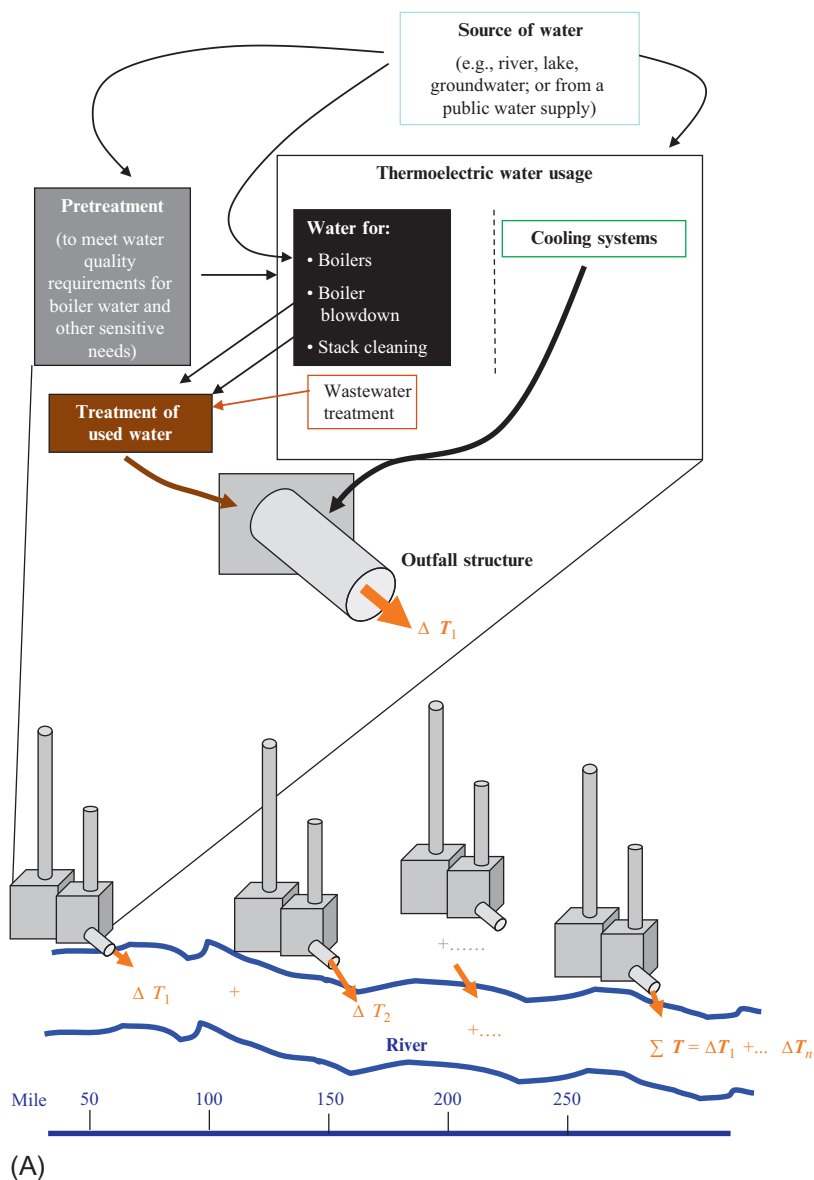


FIG. 20.6 Difference in cumulative heat contribution to a river from electric generating plants using a once-through cooling system (A) versus the same plants using a cooling water return system

(Continued)

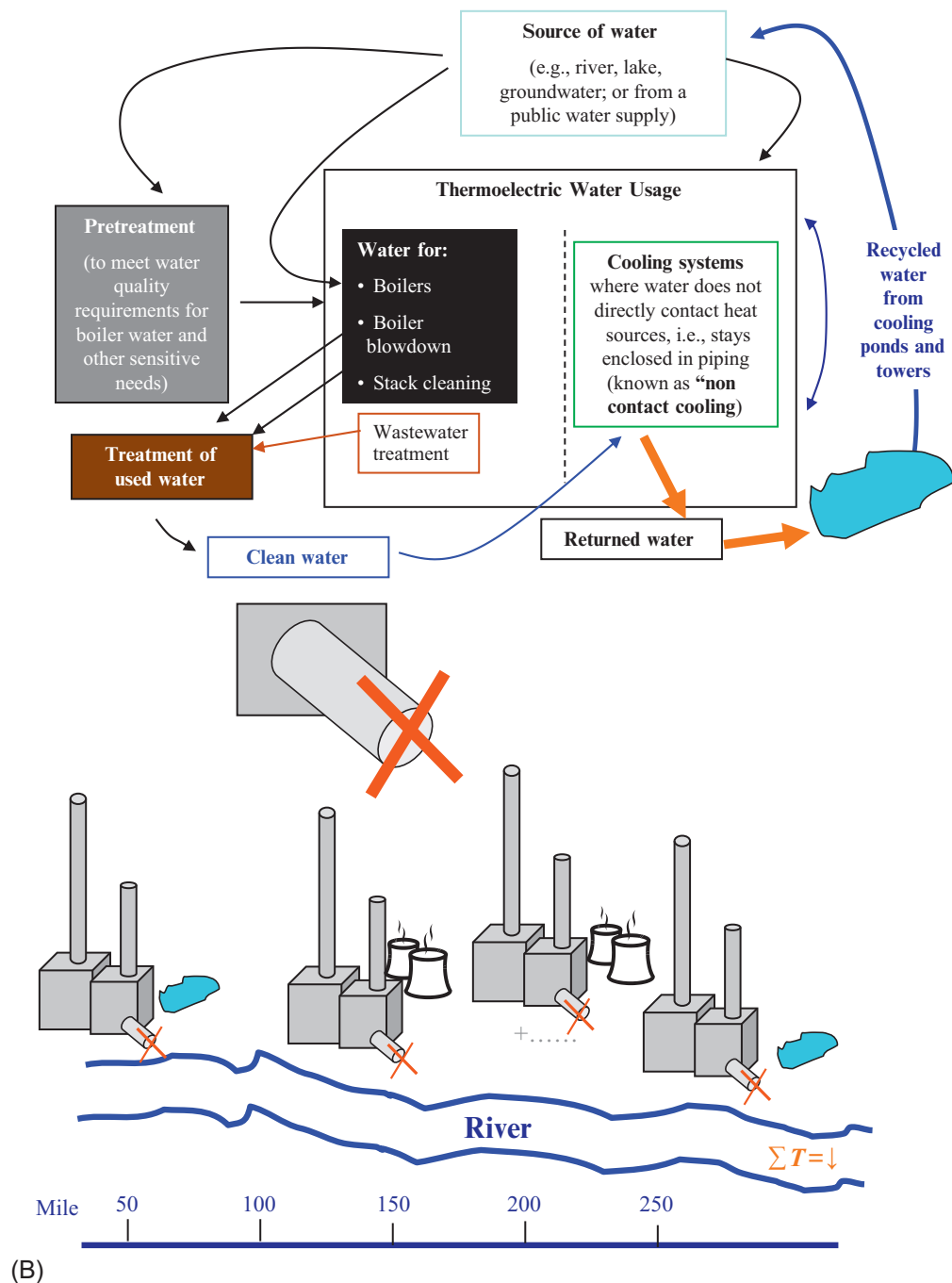


FIG. 20.6—CONT'D (B). The cumulatively added heat is greatly reduced with the closed water return systems compared to the once-through cooling systems (hypothetical scenario). Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015.

Semivolatile organic compounds (SVOCs), notably polycyclic aromatic hydrocarbons (PAHs), dioxins, and furan, are generated under high temperatures of various industrial reactors. Figs. 20.7 and 20.8 show that in a plastics fire, that is, low-density polyethylene pyrolysis, the optimal temperature ranges to form these chemicals differ. The aliphatic compounds in this fire, notably 1-dodecene, 9-nonadecane, and 1-hexacosene, are generated in higher concentrations at lower temperatures (about 800°

C), whereas the aromatics need higher temperatures. The total mass and the total concentrations of these thermally generated compounds continue to increase with temperature, but the speciation changes [15, 16]. This is particularly important to the waste incineration. At some point, the temperature, pressure, sorbent, and oxygen conditions will supplant these compounds to form others that may be even more toxic, for example, the halogenated dioxins and furans. The waste manager must find the

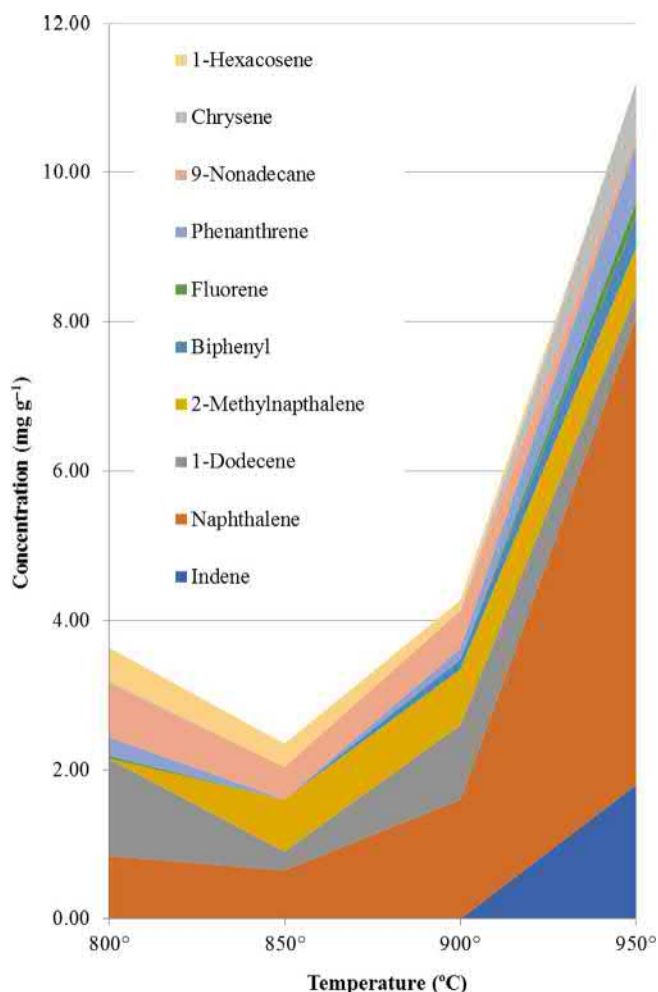
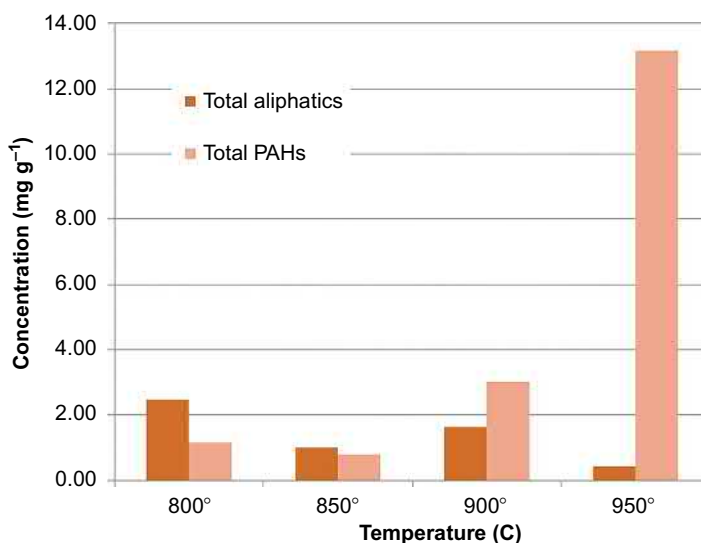


FIG. 20.7 Selected hydrocarbon compounds generated in a low-density polyethylene pyrolysis; low oxygen conditions, in four temperature regions. Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999. Data from R. Hawley-Fedder, M. Parsons, F. Karasek, Products obtained during combustion of polymers under simulated incinerator conditions: I. polyethylene, *J. Chromatogr. A* 314 (1984) 263–273.

FIG. 20.8 Total aliphatic (chain) hydrocarbons versus polycyclic aromatic hydrocarbons (PAHs) generated in a low-density polyethylene pyrolysis in four temperature regions. Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999. Data from R. Hawley-Fedder, M. Parsons, F. Karasek, *Products obtained during combustion of polymers under simulated incinerator conditions: I. polyethylene*, *J. Chromatogr. A* 314 (1984) 263–273.



optimal combination of factors in the thermal process to completely convert as much of the organic mass to nontoxic products [17].

Combustion is used primarily for heat by changing the potential chemical energy of the fuel to thermal energy. This occurs in a fossil fuel-fired power plant, a home furnace, or an automobile engine. Combustion is also used as a means of destruction for our unwanted materials. This decreases the volume of a solid waste by burning the combustibles in an incinerator. The combustion reactor, for example, kiln, accepts combustible solids, liquids, and gases, with undesirable properties such as odors, to a high temperature in an afterburner system to convert them to less objectionable gases. Note that incineration is often used to denote any thermal destruction of waste, but the process covers a large O_2 range. As O_2 concentrations approach zero, pyrolysis dominates, but combustion occurs at higher available O_2 concentrations.

Most greenhouse gases are formed in thermal reactions. In fact, complete combustion means that the most prominent greenhouse gas, carbon dioxide (CO_2), will be released. However, this is just one of the carbon compounds that are cycled continuously biogeochemically through the environment [18, 19] (see Fig. 20.9).

After the release of CO_2 and other carbon compounds, the carbon may remain sequestered in the soil, roots, sediment, and other compartments, released to the atmosphere, or otherwise be cycled throughout the environment. Therefore even a small net addition of greenhouse gases can profoundly increase the atmosphere's greenhouse potential.

Carbon dioxide, CO_2 , is an inorganic compound because its carbon atom does not contain a covalent bond with other carbon or hydrogen atoms. Other important inorganic carbon compounds include the pesticides sodium cyanide ($NaCN$) and potassium cyanide (KCN), as are the toxic gas carbon monoxide (CO). Inorganic compounds also include inorganic acids, such as carbonic acid (H_2CO_3) and cyanic acid ($HCNO$) and compounds derived from reactions with the anions carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-). However, most carbon compounds are organic.

Fig. 20.10 depicts the equilibrium among carbonates, bicarbonates, organic compounds, carbonic acid, and carbon dioxide. On a global scale, uncontaminated rain's mean pH is about 5.6, owing to the CO_2 that has been dissolved in the rain. As the water droplets fall through the air, the CO_2 in the atmosphere becomes

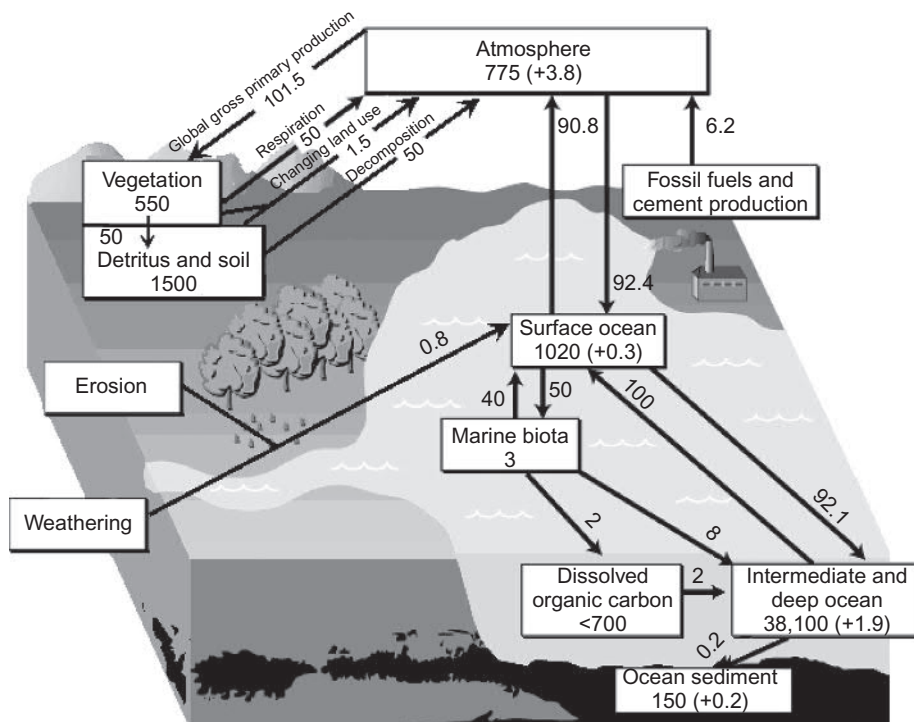


FIG. 20.9 Global carbon cycle from 1992 to 1997. Carbon pool are boxes, expressed in gigatonnes (Gt) of carbon (Note: $\text{Gt} = 10^{15} \text{ g}$). Annual increments are expressed in gigatonnes per annum of carbon (shown in parentheses). All fluxes indicated by the arrows are expressed in Gt a^{-1} of carbon. The inferred net terrestrial uptake of 0.7 Gt a^{-1} of carbon considers gross primary production (~ 101.5), plant respiration (~ 50), decomposition (~ 50), and additional removal from the atmosphere directly or indirectly, through vegetation and soil and eventual flow to the ocean through the terrestrial processes of weathering, erosion, and runoff (~ 0.8). Net ocean uptake (~ 1.6) considers air/sea exchange (~ 92.4 gross uptake, -90.8 gross release). As the rate of fossil fuel burning increases and CO_2 released to the atmosphere it is expected that the fraction of this C remaining in the atmosphere will increase resulting in a doubling or tripling of the atmospheric amount in the coming century. Source: W.M. Post, T.-H. Peng, W.R. Emanuel, A.W. King, V.H. Dale, D.L. DeAngelis, *The global carbon cycle*, *Am. Sci.* 78(4) (1990) 310–326.

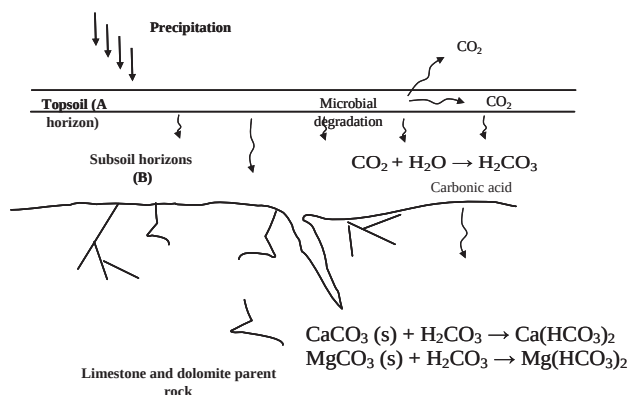
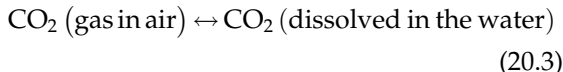
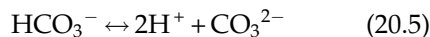
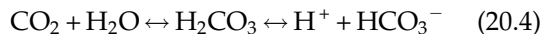


FIG. 20.10 Biogeochemistry of carbon equilibrium. The processes that release carbonates are responsible for much of the buffering capacity of natural soils against the effects of acid rain. Source: D.A. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Academic Press, Amsterdam, NV, 2010.

dissolved in the water, setting up an equilibrium condition:



The CO_2 in the water reacts to produce hydrogen ions, as



Assuming the mean partial pressure CO_2 in the air to be 3.0×10^{-4} atm, it is possible to calculate the pH of water in equilibrium. Heat is not only a factor in the formation of CO_2 , but also as a secondary factor, that is, if the atmosphere is heated it will speed up most reactions. For example, assuming an ambient temperature of 25°C and an adjusted mean concentration of CO_2 in the troposphere of 350 ppm, the temperature assumption would also have to be adjusted if this concentration is rising by some estimates at a rate of 1 ppm per year.

Henry's law states that the concentration of a dissolved gas is directly proportional to the partial pressure of that gas above the solution:

$$p_a = K_H [c] \quad (20.6)$$

where K_H is the Henry's law constant, p_a is the partial pressure of the gas, and $[c]$ is the molar concentration of the gas.

The brackets indicate the chemical concentration in mol L^{-1} . More commonly in environmental publications, concentration is expressed in units of mass per volume, such as:

$$p_a = K_H C_W \quad (20.7)$$

where C_W is the concentration in units of mass of gas per L of water.

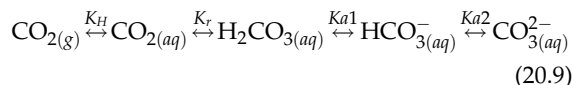
The Henry's Law coefficient is therefore a function of a substance's solubility in water and its vapor pressure and expresses the proportionality between the concentration of a dissolved contaminant and its partial pressure in

the open atmosphere at equilibrium. That is, the Henry's Law constant is an example of an *equilibrium constant*, which is the ratio of concentrations when chemical equilibrium is reached in a reversible reaction. This equilibrium state is attained when the rate of the forward reaction is the same as the rate of the reverse reaction.

The CO_2 concentration of the water droplet at equilibrium with air is obtained from the partial pressure of Henry's law constant:

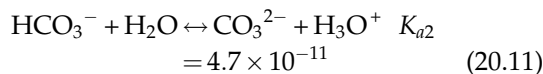
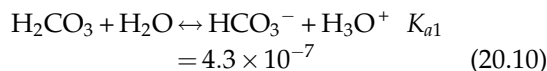
$$p_{\text{CO}_2} = K_H [\text{CO}_2]_{\text{aq}} \quad (20.8)$$

The change from carbon dioxide in the atmosphere to carbonate ions in water droplets follows a sequence of equilibrium reactions:



The processes that release carbonates increase the buffering capacity of natural soils against the effects of acidic water ($\text{pH} < 5$). Thus carbonate-rich soils like those of central North America can withstand even elevated acid deposition compared to the thin soil areas, such as those in the Canadian Shield, the New York Finger Lakes region, and much of Scandinavia.

The concentration of carbon dioxide CO_2 is constant, since the CO_2 in solution is in equilibrium with the air that has a constant partial pressure of CO_2 . And the two reactions and ionization constants for carbonic acid are:



K_{a1} is four orders of magnitude greater than K_{a2} , so the second reaction can be ignored for environmental acid rain considerations. The solubility of gases in liquids can be described quantitatively by Henry's Law, so for CO_2 in the atmosphere at 25°C , we can apply the Henry's

Law constant and the partial pressure to find the equilibrium. The K_H for $\text{CO}_2 = 3.4 \times 10^{-2} \text{ mol L}^{-1} \text{ atm}^{-1}$. The partial pressure of CO_2 is the fraction of CO_2 of all gases in the atmosphere. If CO_2 in the earth's troposphere is 350 ppm by volume in the atmosphere, the fraction of CO_2 must be 350 divided by 10^6 or 0.000350 atm.

Thus the carbon dioxide and carbonic acid molar concentration can now be found:

$$[\text{CO}_2] = [\text{H}_2\text{CO}_3] = 3.4 \times 10^{-2} \text{ mol L}^{-1} \text{ atm}^{-1} \times 0.000350 \text{ atm} = 1.2 \times 10^{-5} \text{ M}$$

The equilibrium is $[\text{H}_3\text{O}^+] = [\text{HCO}_3^-]$. Taking this and our carbon dioxide molar concentration gives us:

$$K_{a1} = 4.3 \times 10^{-7} = \frac{[\text{HCO}_3^-][\text{H}_3\text{O}^+]}{[\text{CO}_2]} = \frac{[\text{H}_3\text{O}^+]^2}{1.2 \times 10^{-5}}$$

$$[\text{H}_3\text{O}^+]^2 = 5.2 \times 10^{-12}$$

$$[\text{H}_3\text{O}^+] = 2.6 \times 10^{-6} \text{ M}$$

Or, the droplet pH is about 5.6.

Thus changes in CO_2 concentrations will change the mean acidity of precipitation. For example, many models expect a rather constant increase in tropospheric CO_2 concentrations. For example, the increase from the present 350 ppm to 400 ppm tropospheric CO_2 concentrations would be accompanied by a proportional decrease in precipitation pH. The molar concentration can be adjusted using the previous equations:

$$3.4 \times 10^{-2} \text{ mol L}^{-1} \text{ atm}^{-1} \times 0.000400 \text{ atm} \\ = 1.4 \times 10^{-5} \text{ M},$$

so

$$4.3 \times 10^{-7} = \frac{[\text{H}_3\text{O}^+]^2}{1.4 \times 10^{-5}}$$

and

$$[\text{H}_3\text{O}^+]^2 = 6.0 \times 10^{-12} \text{ and } [\text{H}_3\text{O}^+] = 3.0 \times 10^{-6} \text{ M}$$

With a 50-ppm increase in CO_2 , average water droplet pH would be decrease to about 5.5. This means that an increase in atmospheric carbon dioxide will result in an increase in the acidity of natural rainfall. The precipitation rates themselves would also be affected if greenhouse gas concentrations continue to increase, so any changes in atmospheric precipitation rates would also, on average, be expected to be more acidic. The forcing factors for these interrelationships are shown in Fig. 20.11. This is an interesting example of the earth acting as a very large reactor. Changing one variable can profoundly change the entire system; in this instance the release of one gas changes numerous physical (e.g., temperature) and chemical (e.g., precipitation pH) factors, which in turn evoke a biological response (biome and ecosystem diversity). This also leads to second-order changes, such as that between two prominent greenhouse gases, carbon dioxide and methane. The increased amounts of CO_2 will likely affect global temperature, which affects biomes and the kinetics within individual ecosystems. Ecological structure, such as tree associations, canopies, and forest floors, as well as wetland structures may change, so that the reduced conditions may increase, with an attendant increase in anaerobic microbial decomposition, meaning greater releases of CH_4 , which would mean increasing global temperatures, all other factors being held constant. However, if greater biological activity and increased photosynthesis is triggered by the increase in CO_2 , and wetland depth is decreased, CH_4 global concentrations would fall, leading to less global temperature rise. Conversely, if this increased biological activity and photosynthesis leads to a decrease forest floor detritus mass, then less anaerobic activity may also lead to lower releases of CH_4 . There will be increases and decreases at various scales, so the net effects on a complex, planetary system is highly uncertain.

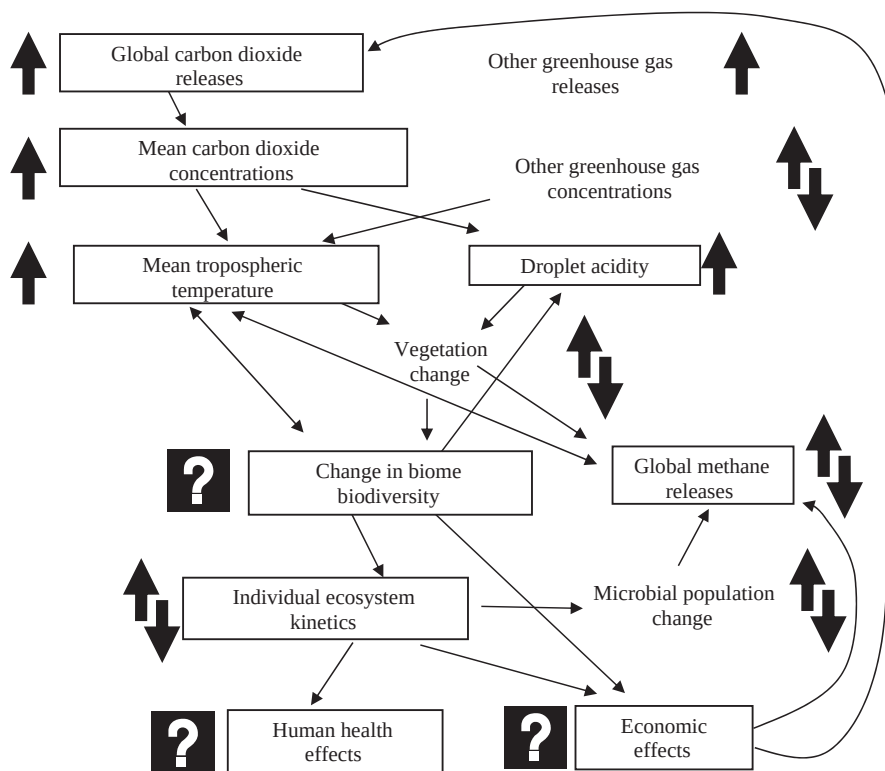


FIG. 20.11 Systematic view of changes in tropospheric carbon dioxide. Thick arrows indicate whether this factor will increase (up arrow), decrease (down arrow) or will vary depending on the specifics (e.g., some greenhouse gas releases have decreased, e.g., the chlorofluorocarbons, and some gases can cool the atmosphere, e.g., sulfate aerosols). Question mark indicates that the type and/or direction of change are unknown or mixed. Thin arrows connect the factors as drivers toward downstream effects. Source: D.A. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Academic Press, Amsterdam, NV, 2010.

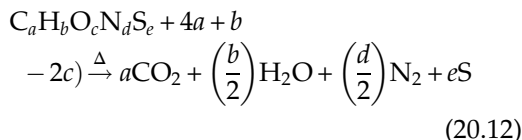
Global warming is a cumulative thermal effect of chemical pollution. That is, as chemicals are added to the atmosphere, the conversion of incoming short-wave radiation to longer-wave infrared radiation is increased, as is the absorption of the heat. Thus the increased concentrations of greenhouse chemicals lead to a thermal effect, that is, surface and atmospheric heating. The uncertainties in predicting the amount of heating include the actual radiative capacity of these chemicals, the cooling effect of other chemicals, for example, sulfates, and the accuracy in giving weights to these and other factors to a very complex atmosphere.

3.2 Thermo-Chemical Formation of Sulfur and Nitrogen Compounds

Much of the concern for acid rain has been rightly concerned about compounds other than CO_2 and CH_4 , notably oxides of sulfur and nitrogen. These also encompass several greenhouse gases with varying radiative forcing in both directions (e.g., sulfates may be net cooling agents via reflection of the sun's rays).

Many compounds contain both nitrogen and sulfur along with the typical organic elements (carbon, hydrogen, and oxygen). The reaction

for the combustion of sulfur and nitrogen compounds in general form is:



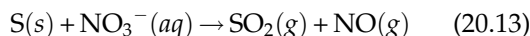
Thermal processes often generate oxides [e.g., sulfur dioxide (SO₂) and nitrogen dioxide (NO₂)]. These, in turn, form acids as they react with water that ultimately causes environmental problems (i.e., acid deposition). Adding such compounds to the environment has both chemical and physical impacts. For example, some soils easily buffer even large amounts of acidic rain, whereas others have very limited buffering capacities. Some organisms have large pH tolerance ranges, whereas others may not be able to withstand even a slight change in pH. Whether a compound will remain in the physical and chemical state in which it was deposited is also dependent on the environmental conditions. In the real world, the environment is filled with mixtures of elements, compounds, substrates, and matrices, so pure reactions are almost never the case.

Reaction (20.12) can be compared to that of complete combustion of a simple hydrocarbon, that is, $C_a H_b + O_2 \xrightarrow{\Delta} CO_2 + H_2O$. Reactions can occur in sequence, parallel, or both. For example, a feedstock to a municipal incinerator usually contains myriad types of wastes, from garbage to household chemicals to commercial wastes, and even small (and sometimes large) industrial wastes that may be illegally dumped. This variability of feedstock can, however, be improved with proper collection, sorting, segregation, and handling, but it never can be completely eliminated.

Even when the feedstock is a single waste stream, there can be considerable variability. For example, the nitrogen content of typical cow manure is about 5 kg per metric tonne (about 0.5%). If the fuel used to burn the waste also contains sulfur along with the organic

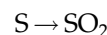
matter, then the five elements will react according to the stoichiometry of reaction (20.12).

Certainly, combustion specifically and oxidation generally are very important processes that generate nitrogen and sulfur pollutants. But they are certainly not the only ones. In fact, we need to explain what oxidation really means. In the environment, oxidation *and* reduction occur. The formation of two sulfur dioxide and nitric oxide by acidifying molecular sulfur is a redox reaction:

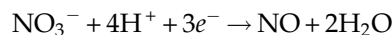
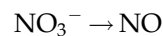


The designations in parentheses give the physical phase of each reactant and product: "s" for solid, "aq" for aqueous, and "g" for gas.

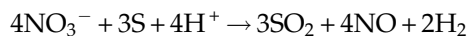
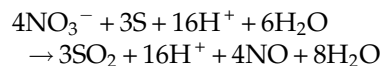
The oxidation half-reactions for this reaction are:



The reduction half-reactions for this reaction are:



Therefore the balanced oxidation-reduction reactions are:



A reduced form of sulfur that is highly toxic and an important pollutant is hydrogen sulfide (H₂S). Certain steps in thermal processes can be anoxic (i.e., lacking O₂) where nitrogen and sulfur are reduced. Thus the release of highly toxic compounds, like H₂S, would be released without proper treatment. In this case, redox principles can be used to treat H₂S contamination. Strong oxidizers, like molecular oxygen and hydrogen peroxide, most effectively oxidize the reduced forms of S, N or any reduced compound.

3.3 Toxic Byproducts

Thermal processes are used to break down harmful molecules into smaller, less harmful molecules. Conversely, these same processes can also lead to the formation of toxic compounds that are even more harmful than the parent compounds in the original waste. Thermal reactions can generate some very toxic byproducts. As an example, chlorinated dioxins consist of 75 different forms and there are 135 different chlorinated furans, delineated by the number and arrangement of chlorine atoms on the molecules. The compounds can be separated into groups that have the same number of chlorine atoms attached to the furan or dioxin ring. There are also numerous other dioxins with varying combinations of halogens, for example, brominated dioxins or bromochlorodioxins. Each form varies in its chemical, physical, and toxicological characteristics (see Fig. 20.12).

Dioxin-like compounds are highly toxic compounds that are created unintentionally during combustion processes. The most toxic form is the 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) isomer. Other isomers with the 2,3,7,8 configuration have also been shown to have higher mammalian toxicity than the dioxins and furans with different chlorine atom arrangements. When describing classes of compounds with numerous congeners, a toxicity equivalence (TEQ) of the mixture is used. For polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans the World Health Organization [20] devised a procedure which translates the complex mixture of chlorinated dioxins and furans characteristic of environmental releases into an equivalent toxicity concentration of 2,3,7,8-TCDD, since it is the most toxic member of this class of compounds. Thus 2,3,7,8-TCDD has a toxicity equivalency factor of 1. The TEQ is calculated as:

$$\text{TEQ} = \sum i - n(\text{Congener } i \times \text{TEF}_i) + (\text{Congener } j \times \text{TEF}_j) + \dots (\text{Congener } n \times \text{TEF}_n) \quad (20.14)$$

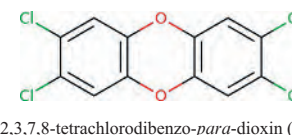
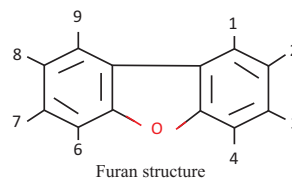
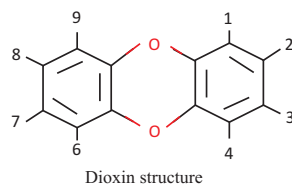


FIG. 20.12 Molecular structures of dioxins and furans. Bottom structure is of the most toxic dioxin congener, tetrachlorodibenzo-*para*-dioxin (TCDD), formed by the substitution of chlorine for hydrogen atoms at positions 2, 3, 7, and 8 on the molecule.

From Table 20.3, the TEF for 2,3,7,8-TCDF is one-tenth that of 2,3,7,8-TCDD and the octachlorinated furan, OCDD, is one-ten thousandth. Thus the total amount of dioxin and furan stress equilibrated to 2,3,7,8-TCDD is indicated by the TEQ, and expressed as TEQ grams (TEQ g).

The chemical and physical mechanisms that lead to the production of dioxin involve chlorine (Cl). Incinerators of chlorinated wastes are the most common environmental sources of dioxins, accounting for about 95% of the volume.

The emission of dioxins and furans from thermal processes may follow three general physicochemical pathways. The first pathway is not a thermal process, but one where the thermal treatment is ineffective. That is, the feed material entering the combustion unit contains dioxins or

TABLE 20.3 Toxicity Equivalency Factors (TEFs) for Chlorinated Dioxin and Furan Congeners

Dioxin Congener	TEF	Furan Congener	TEF
2,3,7,8-TCDD	1	2,3,7,8-TCDF	0.1
1,2,3,7,8-PeCDD	1	1,2,3,7,8-PeCDF	0.05
1,2,3,4,7,8-HxCDD	0.1	2,3,4,7,8-PeCDF	0.5
1,2,3,6,7,8-HxCDD	0.1	1,2,3,4,7,8-HxCDF	0.1
1,2,3,7,8,9-HxCDD	0.1	1,2,3,6,7,8-HxCDF	0.1
1,2,3,4,6,7,8-HpCDD	0.01	1,2,3,7,8,9-HxCDF	0.1
OCDD	0.0001	2,3,4,6,7,8-HxCDF	0.1
		1,2,3,4,6,7,8-HpCDF	0.01
		1,2,3,4,7,8,9-HpCDF	0.01
		OCDF	0.0001
Chemical Structure	IUPAC Number	TEF	
3,3',4,4'-TCB	PCB-77	0.0001	
3,4,4',5-TCB	PCB-81	0.0001	
2,3,3',4,4'-PeCB	PCB-105	0.0001	
2,3,4,4',5-PeCB	PCB-114	0.0005	
2,3',4,4',5-PeCB	PCB-118	0.0001	
2',3,4,4',5-PeCB	PCB-123	0.0001	
3,3',4,4',5-PeCB	PCB-126	0.1	
2,3,3',4,4',5-HxCB	PCB-156	0.0005	
2,3,3',4,4',5'-HxCB	PCB-157	0.0005	
2,3',4,4',5,5'-HxCB	PCB-167	0.00001	
3,3',4,4',5,5'-HxCB	PCB-169	0.01	
2,3,3',4,4',5,5'-HpCB	PCB-189	0.0001	

Source: U.E.P. Agency, *An Inventory of Sources and Environmental Releases of Dioxin-Like Compounds in the United States for the Years 1987, 1995, and 2000*, National Technical Information Service, Washington, DC, 2006.

furans and a fraction of these compounds survives thermal breakdown mechanisms, passes through, and is to be emitted from vents or stacks. This is not considered to account for

a large volume of dioxin released to the environment, but it may account for the release of some dioxin-like, coplanar polychlorinated biphenyls (PCBs) from incinerators.

Dioxins and furans can also be formed during the thermal breakdown and molecular rearrangement of precursor compounds, such as the chlorinated benzenes, chlorinated phenols (e.g., pentachlorophenol), and PCBs, which are chlorinated aromatic compounds with chemical structures similar to those of the chlorinated dioxin and furan molecules. Dioxins may well form after the precursor has condensed and is adsorbed onto the surface of particles, such as fly ash. This heterogeneous process occurs on the active sorption sites on the particles, allowing for the chemical reactions that are catalyzed by the presence of inorganic chloride compounds and ions sorbed to the particle surface. The process occurs within the range of 250–450°C, so most of the dioxin formation under the precursor mechanism takes place away from the high temperature zone in the incinerator. This is where the gases and smoke derived from combustion of the organic materials have cooled during conduction through flue ducts, heat exchanger and boiler tubes, air pollution control equipment or the vents and the stack.

The third means of synthesizing dioxins ensues as a *de novo* process within the so-called cool zone of the incinerator. Here, the dioxins and furans form from moieties different from those of the molecular structure of dioxins, furans, or precursor compounds. Generally, these can include a wide range of both halogenated compounds like polyvinylchloride (PVC), and nonhalogenated organic compounds like petroleum products, nonchlorinated plastics (polystyrene), cellulose, lignin, coke, coal, and inorganic compounds like particulate carbon, and hydrogen chloride gas. No matter which *de novo* compounds are involved a chlorine atom must be donated to the reaction, which leads to the formation and chlorination of a chemical intermediate that is a precursor.

The reaction steps, after this precursor is formed, can be identical to the precursor mechanism discussed in the previous paragraph [21].

De novo formation of dioxins and furans may involve even more fundamental substances than those moieties mentioned before. For example, dioxins may be generated by heating of carbon particles absorbed with mixtures of magnesium-aluminum silicate complexes when the catalyst copper chloride (CuCl_2) is present [22](see Table 20.4 and Fig. 20.13). The de novo formation of chlorinated dioxins and furans from the oxidation of carbonaceous particles seems to occur at around 300°C. Other

chlorinated benzenes, chlorinated biphenyls, and chlorinated naphthalene compounds are also generated by this type of mechanism.

Other processes generate dioxin pollution. A source that has been greatly reduced in the last decade is the paper production process, which formerly used chlorine bleaching. This process has been dramatically changed, so that most paper mills no longer use the chlorine bleaching process. Dioxin is also produced in the making of PVC plastics, which may follow chemical and physical mechanisms like the second and third processes discussed before.

Specific to thermal processes employed for waste management, toward the end of the 20th century, municipal waste incineration was the largest source of dioxin emissions in the United States. However, with better controls and management, this dropped to the fourth largest. Domestic refuse burning, for example, backyard barrels, remained steady and became the largest by the year 2000, representing 35% of dioxin-like compound emissions, that is, about 500 g TEQ per year (see Table 20.5).

Since all dioxin and dioxin-like compounds are lipophilic and persistent, they accumulate in soils, sediments, and organic matter and can persist in solid and hazardous waste disposal sites [23–26]. These compounds are semivolatile, so they may migrate away from these sites and be transported in the atmosphere either as aerosols (solid and liquid phase) or as gases (the portion of the compound that volatilizes). Therefore the engineer must take great care in removal, and remediation efforts not to unwittingly cause releases from soil and sediments via volatilization or via perturbations, such as landfill and dredging operations.

Incineration is frequently used to decontaminate solid matrices, for example, soils, with elevated concentrations of organic hazardous constituents. Many of these substances can be completely combusted at much lower temperatures than larger, more recalcitrant compounds like the dioxins. For example, high-temperature incineration may not be needed to treat wastes

TABLE 20.4 De Novo Formation of Chlorinated Dioxins and Furans After Heating Mg—Al Silicate, 4% Charcoal, 7% Cl, 1% $\text{CuCl}_2 \cdot \text{H}_2\text{O}$ at 300°C

Compound	Concentrations (ng g^{-1})				
	Reaction Time (h)				
	0.25	0.5	1	2	4
Tetrachlorodioxin	2	4	14	30	100
Pentachlorodioxin	110	120	250	490	820
Hexachlorodioxin	730	780	1600	2200	3800
Heptachlorodioxin	1700	1840	3500	4100	6300
Octachlorodioxin	800	1000	2000	2250	6000
Total chlorinated dioxins	3342	3744	7364	9070	17,020
Tetrachlorofuran	240	280	670	1170	1960
Pentachlorofuran	1360	1670	3720	5550	8300
Hexachlorofuran	2500	3350	6240	8900	14,000
Heptachlorofuran	3000	3600	5500	6700	9800
Octachlorofuran	1260	1450	1840	1840	4330
Total chlorinated furans	8360	10,350	17,970	24,160	38,390
Total chlorinated furans	8360	10,350	17,970	24,160	38,390

Note: ng = nanogram.

Source: L. Stieglitz, G. Zwick, J. Beck, H. Bautz, W. Roth, *The role of particulate carbon in the de-novo synthesis of polychlorinated dibenzodioxins and-furans in fly-ash*, *Chemosphere* 20(10–12) (1990) 1953–1958; L. Stieglitz, G. Zwick, J. Beck, H. Bautz, W. Roth, *Carbonaceous particles in fly ash—a source for the de-novo-synthesis of organochloro compounds*, *Chemosphere* 19(1–6) (1989) 283–290.

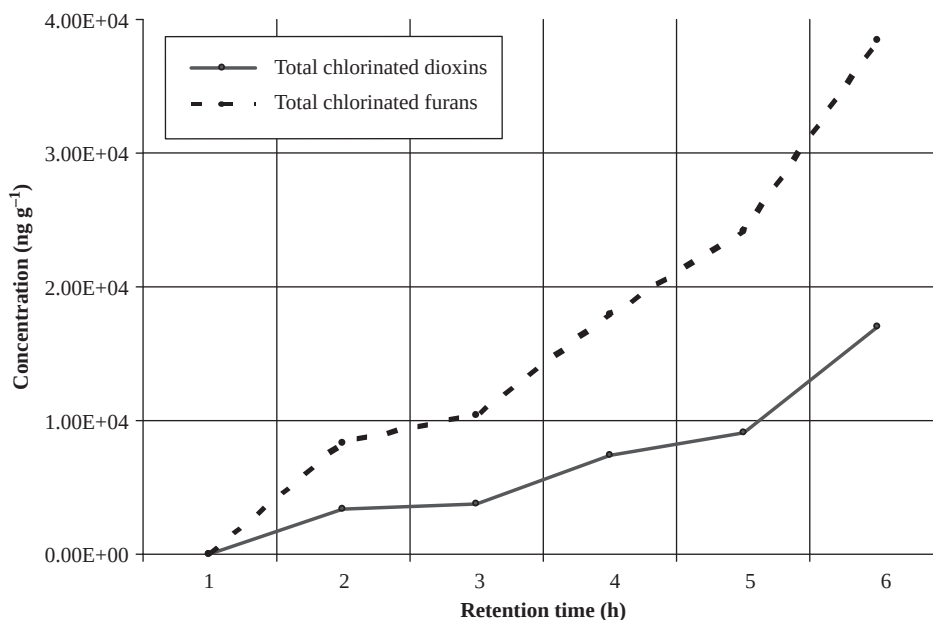


FIG. 20.13 De novo formation of chlorinated dioxins and furans after heating Mg—Al silicate, 4% charcoal, 7% Cl, 1% CuCl₂·H₂O at 300°C. Note: ng = nanogram. Sources: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999; L. Stieglitz, G. Zwick, J. Beck, H. Bautz, W. Roth, *The role of particulate carbon in the de-novo synthesis of polychlorinated dibenzodioxins and-furans in fly-ash*, *Chemosphere*, 20(10–12) (1990) 1953–1958.

contaminated with many volatile organic compounds (VOCs). In addition, high-temperature incineration of wastes with heavy metals will likely increase the volatilization of some of these metals into the combustion flue gas (see [Tables 20.6 and 20.7](#)). High concentrations of volatile trace metal compounds in the flue gas poses increased challenges to air pollution control. Thus other thermal processes, that is, thermal desorption and pyrolysis, can provide an effective alternative to incineration.

When successful in decontaminating wastes to the necessary treatment levels, thermally desorbing contaminants from the solid matrix has the additional benefits of lower fuel consumption, no formation of slag, less volatilization of metal compounds, and less complicated air pollution control demands. So, beyond monetary costs and ease of operation, a less energy (heat)

intensive system can be more advantageous in terms of actual pollutant removal efficiency.

4 CONCLUSIONS

Waste management often involves the application of thermodynamic principles and the appreciation of heat's importance. No environmental system can be fully understood without ample knowledge of temperature. Every chemical reaction is affected by temperature. The difference between complete destruction of a toxic compound and the generation and release of compounds that are even more toxic than the original waste constituent can be determined by relatively small temperature ranges.

Adding heat to a stream or other ecosystem can completely alter its biological integrity. Food

TABLE 20.5 Decrease in Emissions of Dioxin-Like Compounds (in the United States From the Year 1987 to Year 2000)

Source Category	Releases to	2000 (g TEQ)	1987 (g TEQ)	Percent Reduction
Municipal waste combustion	Air	83.8	8905	>99
Medical waste incineration	Air	378.0	2570	85
Cement kilns burning hazardous waste	Air	18.8	118	84
Bleached chemical wood pulp and paper mills	Surface water	1.0	356	>99

Source: U.E.P. Agency, *An Inventory of Sources and Environmental Releases of Dioxin-Like Compounds in the United States for the Years 1987, 1995, and 2000*, National Technical Information Service, Washington, DC, 2006.

TABLE 20.6 Conservative Estimates of Heavy Metals and Metalloids Partitioning to Flue Gas as a Function of Solids Temperature (t) and Chlorine Content

Metal or Metalloid	T = 871°C		T = 1093°C	
	Cl = 0%	Cl = 1%	Cl = 0%	Cl = 1%
Antimony	100%	100%	100%	100%
Arsenic	100%	100%	100%	100%
Barium	50%	30%	100%	100%
Beryllium	5%	5%	5%	5%
Cadmium	100%	100%	100%	100%
Chromium	5%	5%	5%	5%
Lead	100%	100%	100%	100%
Mercury	100%	100%	100%	100%
Silver	8%	100%	100%	100%
Thallium	100%	100%	100%	100%

Note: The remaining percentage of metal is contained in the bottom ash. Partitioning for liquids is estimated at 100% for all metals. The combustion gas temperature is expected to be 40–500°C higher than the solids temperature.

Source: U.S. Environmental Protection Agency, *Handbook: Guidance on Setting Permit Conditions and Reporting Trial Burn Results*, EPA 625/6-89-019, 1989.

TABLE 20.7 Metal and Metalloid Volatilization Temperatures

Metal or Metalloid	Without Chlorine		With 10% Chlorine	
	Volatility Temperature (°C)	Principal Species	Volatility Temperature (°C)	Principal Species
Chromium	1613	CrO ₂ /CrO ₃	1611	CrO ₂ /CrO ₃
Nickel	1210	Ni (OH) ₂	693	NiCl ₂
Beryllium	1054	Be (OH) ₂	1054	Be (OH) ₂
Silver	904	Ag	627	AgCl
Barium	841	Ba (OH) ₂	904	BaCl ₂
Thallium	721	Tl ₂ O ₃	138	TlOH
Antimony	660	Sb ₂ O ₃	660	Sb ₂ O ₃
Lead	627	Pb	–15	PbCl ₄
Selenium	318	SeO ₂	318	SeO ₂
Cadmium	214	Cd	214	Cd
Arsenic	32	As ₂ O ₃	32	As ₂ O ₃
Mercury	14	Hg	14	Hg

Source: B.C. Willis, M.M. Howie, R.C. Williams, *Public Health Reviews of Hazardous Waste Thermal Treatment Technologies: A Guidance Manual for Public Health Assessors*, US Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, 2002.

chains and the health of human populations are affected by direct heating or by the indirect effects of added heat. Thus waste managers must always devote attention to these and other possible impacts from heat in the design and operation of systems.

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Microplastics: Emerging Contaminants Requiring Multilevel Management

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OUTLINE

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1 INTRODUCING MICROPLASTIC

Recently discovered and widely distributed, microplastics are tiny plastic particles which measure less than five millimeters on their longest axis. Currently known as a common pollutant of both aquatic and terrestrial environments, the increasing abundance of small plastics was first recognized in 2004, following observations of rising numbers of microplastics in marine plankton samples collected from 1960 onward [1]. Despite the relatively recent discovery of

microplastics and their distribution, increasing reports of microplastic contamination, uptake and impacts on organisms have resulted in concern from the scientific community, conservation bodies, and the general public [2–4].

The formation and abundance of microplastic debris is intrinsically linked to global polymer production and the abundance of macroplastic materials. Since their development in the 1950s, plastics have become essential in the production of both domestic and industrial goods. Over the past 50 years, polymer production

has increased from a mere 1.5×10^6 t (1.5 million tonnes) in 1964, to over 350×10^6 t in 2015. In the same period, the accidental and intentional introduction of plastics into the environment has resulted in a level of macroplastic debris which is both esthetically and environmentally damaging in its own right.

The presence of such plastics in domestic and industrial waste is well documented, with reports of plastics recovered from locations as remote and varied as deep-sea sediments and mountainsides [5, 6]. Records of plastics persisting the environment include those of the earliest, naturally derived polymers, retrieved from the wreck of the Titanic which sunk in 1912 [7]. Observations of more modern polymers in remote habitats can be found as early as the 1970s [8].

As global understanding of polymer chemistry has developed over the past 70 years, so the number and diversity of polymers and their additives has risen, enabling manufacturers to develop plastics with a broad range of properties and applications. It is the diverse range of physical properties exhibited by plastic polymers that is key to the proliferation of plastic as a component of both industrial and consumer goods. Plastics are now essential components of electronics, furniture, vehicles, and innumerable other products.

The use of plastic in such a large range of products, coupled with the rate of population growth has resulted in an increasing mass of potential debris. Of the 25.8×10^6 t (25.8 million tonnes) of plastic waste produced in 2014, only 69% was recovered with 31% going to landfill [9]. However, this does not account for the abandoned, lost, and discarded plastic released to the environment; the subsequent breakdown of which may take many hundreds of years [10].

As plastics are introduced into the environment at a rate much greater than that at which they degrade, the mass of plastic pollution increases annually. Fragmentation of macroplastic results in the formation of microplastics

[11]; as the polymer structure is not affected by this physical fragmentation, these microplastic may also persist for hundreds of years. The effects of this are observable in the increasing proportion of microplastic in relation to other types of marine litter.

2 CLASSIFYING MICROPLASTIC

Due to their numerous sources and often irregular forms, microplastics can be hard to define. Even their upper size limit is currently under debate, with increasing numbers of studies advocating a more environmentally and functionally relevant maximum length of just 1 mm. Microplastics are nominally separated into two distinct sources; *primary microplastics*, which are those manufactured below five (or one!) millimeters in size, and *secondary microplastics*, those formed due to the fragmentation of larger macroplastics or “parent material.” Sources of primary microplastics include the feedstock for the plastic manufacturing process (nibs, nurdles, and powder); scrubbing particles in cosmetic goods, household cleaning products; glitter; and shot blasting media. The loss of many of these particles is the result of mishandling in transport and subsequent release into either drainage water or sewer systems [12]. Currently, modern water treatment plants are not capable of completely removing small, inert particles like microplastics, as a result, many microplastics in domestic waste water pass into water courses (Fig. 21.1).

Secondary microplastics may be separated into those formed from plastics during the useful life span of the parent material and those formed following its loss to the environment. Secondary microplastics sources include abrasion of car tires, the wear of boat rigging and of fishing gear during operation, and the formation of microfibers during domestic clothes washing. The latter has only recently come to light as a significant contributor to global



FIG. 21.1 Plastic pellets stranded on a beach in North Ayrshire, Scotland.

microplastic pollution. Synthetic fibers are common in the production of clothing throughout the world, and the action of washing results in the fragmentation of fibers within the garment (Fig. 21.2). Studies have shown that the weekly wash may result in hundreds of thousands of fibers being released from the washing machine. From here they travel to water treatment plants; as with cosmetic scrubs, the treatment process is not sufficient to capture these particles, so many are lost to our watercourses.

Secondary microplastics derived from lost or discarded parent material may be formed by weathering, frictional and shear forces, and the action of organisms. Ultraviolet radiation, temperature, and water can all react with the polymer chain to break it into smaller, more reactive lengths, which may be broken down further by weathering or enzymatic activity [10, 13]; however, the abundance of these factors varies significantly in relation to geographic location, season, burial, and submersion. Samples of



FIG. 21.2 Microfiber (2.5 mm in length) recovered from the stomach of spider crab, *Maja squinado*, caught in the Irish Sea.

polymer ropes exposed to benthic conditions in the Clyde Sea for 8 months indicated degradation related to temperature and UV exposure, and showed evidence of surface damage by grazing invertebrates [11]. In a similar experiment, strips of high-density polyethylene, polypropylene, and extruded polystyrene exposed to saltmarsh conditions for 32 weeks indicated biofilm formation and associated grazing by periwinkles (*Littoraria irrorata*). Observations of the plastic surface using scanning electron microscopy revealed surface erosion, cracking, and pitting, and the authors suggest that delamination is a key route of plastic degradation [14]. Fragmentation of polystyrene has also been observed in the creation of microplastic by boring crustaceans in polystyrene floats [15].

3 INTRODUCTION OF MICROPLASTICS AND MACROPLASTIC PARENT MATERIAL TO THE ENVIRONMENT

Improper handling and disposal of both macroplastic parent material and microplastics results in their introduction to terrestrial and aquatic environments. They may be introduced directly through littering, disposal in wastewater, or accidental loss during transport or handling. They may also be passively distributed, transported to new areas through numerous processes including windblown movement, incorporation into mobile substrates, runoff, and aquatic currents.

In terrestrial habitats, the primary routes of plastic contamination are direct littering and the influx of windblown plastics. Plastics may also be directly introduced during the spreading of contaminated compost. Plastics accidentally included in wastes and sent to composting facilities may not be removed during the screening process. As a result, the finished compost may contain both large plastic debris that may

fragment once released to the environment or previously fragmented microplastics, which will become available throughout the treated area. Similarly, sewage sludge from waste water treatment works may also be used as fertilizer, effectively redirecting plastics destined for aquatic habitats to agricultural land [16]. Terrestrial microplastics may be confined to a small area, becoming buried under deposited organic matter or be redistributed during bioturbation of soils or transported out of the terrestrial environment, resulting in their entrainment in aquatic habitats.

There has been greater study of plastics in freshwater habitats ecosystems. The introduction of microplastics into freshwater environments may occur via littering, windblown debris, runoff, and waste water treatment works. A proportion of plastics in sewage may be caught during treatment and analysis of the levels of microplastics in sewage sludge [17]; however, releases from a secondary treatment plant are predicted to represent the release of 65 million microplastics every day [18]. In the Netherlands, water release from water treatment works revealed between 0.2 and $66 \mu\text{g L}^{-1}$ [19].

In Europe, microplastics have been observed in the Seine [20], Rhine [21], and Danube [22], and in North America in the St. Lawrence River [23]. Microplastics have also been seen in lentic habitats including subalpine Lake Garda, Italy [24], Lake Ontario [25], and Lake St. Francis [23], Canada. Longitudinal assessment of microplastic contamination in the sediment of the St. Lawrence river (from Lake St. Francis to Quebec City) has indicated microplastic presence at all 10 sites, distributed along 320 km [23]. In the Danube, drift net samples collected over 2 years revealed mean plastic abundance of 316.8 items per km^3 and its mass was 4.8 g km^{-3} ; this resulted in an estimated daily input into the Black Sea of 4.2 t [22].

If entering a lentic environment, such as a lake or pond, microplastics may become

permanently deposited in benthic sediments; however, those plastic entering rivers will be subjected to ongoing redistribution. Riverine transport is predominantly unidirectional, from the source of the river toward a confluence or the sea. The rate of this transport is related to flow, the presence of eddies and other slow water areas, and vegetation. In freshwater, a lower proportion of polymers are positively buoyant (as the salt in seawater increases a plastic's relative buoyancy), as a result, more plastics will settle out in slow moving areas.

The transport of plastic and microplastic from terrestrial to riverine systems, and the subsequent downstream movement of contaminated water has resulted in increasing influxes of microplastic in marine environments. Coastal zones are also subject to the effects of windblown debris, direct littering, and wastewater disposal described before. As a result, marine and coastal environments are a sink for much of our discarded plastic. In brackish water habitats, particularly estuaries close to areas of anthropogenic activity the mixing of marine and freshwater plastic sources often result in high levels of microplastic contamination. Notably high microplastic abundances have been observed in the sediments of the lagoon of Venice, Italy. Here concentrations in dry sediment ranged between 2175 and 672 microplastics kg^{-1} , with highest abundances observed in landward areas [26].

Plastics have also been observed in mangrove habitats in the intertidal forests around of Singapore [27], in the coastal waters of Qatar [28], coastal sediments and surf zone of South Africa [29], waters around Japan [30, 31], and in arctic sea ice around Norway [32]. Offshore, microplastics may be transported for long distances by ocean currents, and the microplastic found in a country's waters may not have originated within its borders. For example, Isobe et al. [31] identify a higher proportion of mesoplastics in Japanese waters upstream of the north-eastward currents, suggesting that they originated in the Yellow Sea and East China Sea.

4 PARTITIONING OF MICROPLASTIC IN THE MARINE ENVIRONMENT

As indicated in the previous section, the movement of microplastic in terrestrial and riverine habitats is relatively simplistic. In marine environments, the transport of microplastics is a complex; a three-dimensional puzzle of interacting forces, from the microscale influences of wind to the effect of the earth's rotation [33].

The chemical structure of many polymers results in a specific gravity lower than that of sea water. This indicates that they are less dense than the surrounding liquid and are therefore positively buoyant. Unsurprisingly, observations of plastics in environmental samples have revealed higher proportions of low density polymers in the water column and higher proportions of high density polymers in sediments [34].

The influence of polymer density on vertical microplastic distribution varies with local conditions. Both riverine and marine habitats exhibit varying degrees of water transport. Slow moving water has lower energy and plastics denser than the surrounding solution are more likely to be deposited. In areas of faster or more turbulent water, plastics are more easily carried or resuspended. Areas of lower salinity will also exhibit increased plastic deposition as the relative density of plastics will be increased.

Due to the dynamic nature of marine habitats and the longevity of plastics, it is predicted that microplastics will undergo successive deposition and refloatation. Storm events are known to increase the abundance of high density microplastic in the water column; increased wave energy disturbs sediments, refloating any plastics trapped beneath [35]. Similarly, the passage of fishing gear disturbs the benthos, creating a plume of resuspended sediment and microplastics. The buoyancy of low density polymers is also affected by the presence of colonizers. Particles may accumulate algal films while in the surface waters which cause them to sink [34]. As the

algae die off in deeper water, they are removed, and the plastic returns to its position higher in the water column. As a result, plastics may yo-yo in the water column over an extended period.

In addition to the variation in vertical distribution in the water column, microplastic movement and abundance varies horizontally. Horizontal transport is predominantly driven by the movement of water. In the open oceans, the bulk transport of water (and therefore plastic) is dictated by the global conveyor and the movement of the gyres [36]. These currents herd microplastics, driving them to the gyre center in what is known as “convergence zones.” This effect is so pronounced that many gyres encircle “garbage patches,” which have concentrations of debris much larger than that in the surrounding waters (Fig. 21.3).

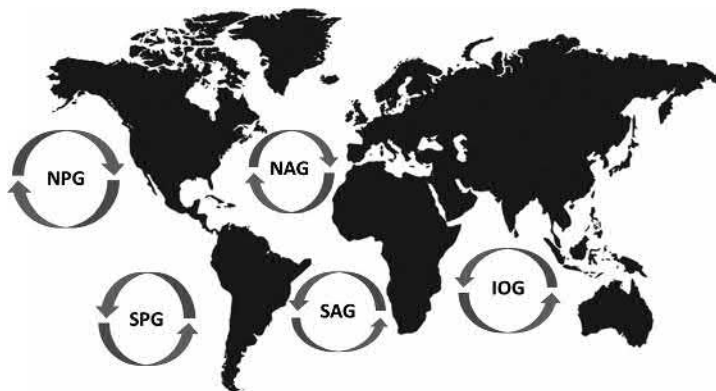
Plastics floating partially above the water’s surface are also subjected to the influence of wind movement. As with ocean currents, there are predominant global wind patterns; however, changes in air pressure temporarily alter wind currents and their influence on microplastic distribution. Plastics riding slightly above the water’s surface will present a surface that is subject to the frictional forces of wind over the water’s surface [33]. If the direction of the wind is different to that of the water, plastics will travel at an angle the current, rather like a sailboat.

Wind direction in coastal areas also dictates which beaches plastics will accumulate on, with onshore breezes increasing the amount of plastic that becomes stranded. Longshore drift, the pattern of zigzagging beach transport caused by waves approaching the shore at an angle, is also responsible for herding plastics and other debris along the shore. Accumulation points then occur at man-made and natural features such as groynes and cliffs which block onward transport. So-called pocket beaches which are highly concave demonstrate comparable conditions and accumulate greater abundances of plastic debris as they are less susceptible to the cleaning effects of longshore drift [37].

5 ENVIRONMENTAL AND HEALTH RISKS

Despite their prevalence in the environment, the potential impacts of microplastics on both organisms and habitats are only vaguely quantified. Microplastics have been observed in the stomachs of species between a few millimeters and over 10m in length, with contamination most regularly reported in organisms from marine and estuarine habitats, where the increasing abundance of microplastic was initially observed. However, more recent reports describe observations of microplastic uptake

FIG. 21.3 Rotation of the gyres and position of the major garbage patches. *NPG*, North Pacific Gyre; *SPG*, South Pacific Gyre; *NAG*, North Atlantic Gyre; *SAG*, South Atlantic Gyre; *IOG*, Indian Ocean Gyre.



in animals from both freshwater and terrestrial environments.

There are numerous potential routes of microplastic uptake. Species may take in plastic during contact with contaminated sediments, respiration, or routine feeding activities. Uptake may be selective in organisms seeking planktonic prey or passive in unselective organisms such as detritivores; they may be taken in directly from the surrounding environment, or during the consumption of contaminated prey. As the concentrations of microplastics in the environment rise, so interactions between organisms and microplastic particles will become more frequent; as a result, many species may be at risk of regular microplastic uptake and its associated impact. The following sections summarize the existing data on the interactions between microplastic and biota.

5.1 Interactions Between Microplastics and Invertebrates

Invertebrates are a diverse group of multicellular organisms, which represent a range of feeding modes—including filterers, detritivores, and predatory species—as well as fulfilling numerous ecosystem services. Microplastic uptake has been observed in numerous invertebrate species from both terrestrial and aquatic environments. The manner in which these species feed and the habitat in which they live has a great influence over the number and type of microplastic with which they interact. Some of the animals most regularly seen to ingest plastics are deposit feeders and filterers.

Filtering species which routinely screen particles from the water column are thought to be at high risk of microplastic ingestion. Food and plastic may be collected either by way of mobile arms or other appendages which are equipped with setae or other fine, hair-like filaments, or water may pass through a siphon with both

plastic and food items continually passing through the animal's gut cavity. This form of feeding is generally unselective, and the uptake of plastic is believed to be unintentional. In mesocosm experiments of microplastic uptake by coastal community assemblages, filtering bivalves demonstrated highest plastic uptake when compared to free-swimming crustaceans and deposit feeders (Setälä et al. [38]). In the wild, both mussels and oysters have been identified as consumers of microplastic. Blue mussels sampled from European coastlines were seen to contain an average of 0.2 microplastics g^{-1} [39], whereas those sampled from 22 sites along the Chinese coast revealed 2.7 microplastics g^{-1} [40]. Highest abundances were observed in areas close to intense human activities and microfibers were the most abundant plastic found [40]. Other filterers known to consume microplastic include crustaceans, such as copepods and other zooplankton [41, 42] and gooseneck barnacles [43], scleractinian corals [44], and filtering sea cucumbers [45].

Deposit feeders and detritivores are also known to take in plastic, ingesting particles with contaminated sediments and detritus. Consumption has been recorded in Annelid worms from aquatic [39] and terrestrial environments [46]; detritivorous crustaceans including shrimps [1, 47], sandhoppers [48], and larger crabs and lobsters [49]. In the wild, observations of Brown shrimp, *Crangon crangon*, from the Channel area and Southern North Sea contained microplastics. The most common type of plastics were fibers, which were detected in 63% of samples [50]. Similarly, *Nephrops norvegicus* sampled from three sites around the coast of Scotland were found to be contaminated [49]. In areas close to high population densities, the microplastic ingestion was observed in 83%–84% of individuals, mostly tangled balls of fibers (Fig. 21.4) [49, 51]. Further away from human activity, the proportion of individuals which contained plastic was below 40%, and no further boluses were observed [49].

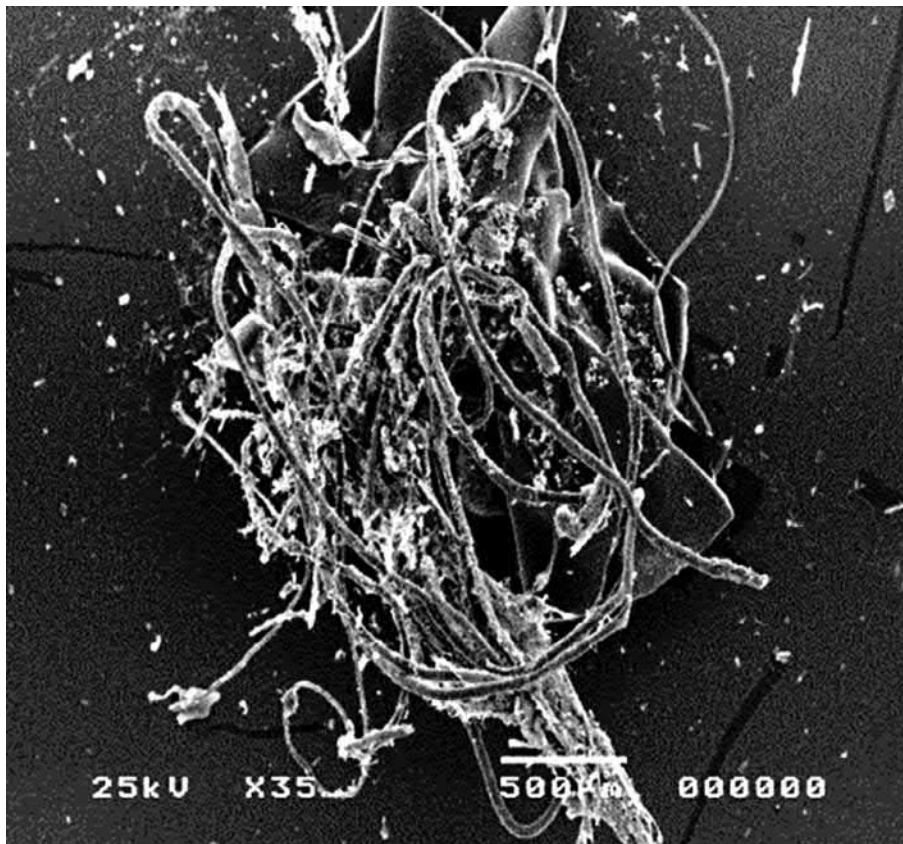


FIG. 21.4 Scanning electron microscope image of microplastic fibers retained by *Nephrops norvegicus*.

Deposit feeding sea cucumbers have also shown the uptake of polyamide and PVC fragments. Comparisons with filter feeding sea cucumbers indicate that deposit feeders are at higher risk of microplastic ingestion, with a higher maximum number of plastic particles consumed by deposit feeding individuals [45]. However, the opposite of this was observed in mesocosm experiments, carried out by Setälä et al., in which microplastic uptake was highest in filtering bivalves, followed by free-swimming crustaceans and deposit feeders [38]. Such discrepancies may be the result of researchers employing different polymers within their trials.

In addition to direct uptake, plastics may be transferred within the food chain. The potential

for trophic transfer in planktonic communities was examined by observing the uptake of microspheres by mysid shrimp fed zooplankton known to have ingested microspheres; the presence of microspheres in the gut of mysids was observed after 3 h. [42]. Microplastic transfer has also been observed between filtering organisms and their predators, for example *Mytilus edulis* fed 0.5- μm fluorescent polystyrene microspheres were fed to shore crabs, *Carcinus maenas*; subsequent examination of crabs resulted in the transfer of up to 0.04% of the plastic to which the mussels were exposed [52]. Trophic transfer of microplastic increased the likelihood of microplastic uptakes by predatory species and may result in bioaccumulation in the food chain.

5.2 Interactions Between Microplastics and Vertebrates

Microplastic ingestion has also been recorded in a range of vertebrate species. As with invertebrates, the species of fish seen to contain microplastics represent different feeding strategies and originate in varied habitats. To date, the studies carried out in the marine and freshwater environment have predominantly concerned fish rather than invertebrates [53], mammals, and birds. When the relative number of species of fish is compared to that of invertebrates, this difference appears vastly disproportionate; this is most likely to be due to the availability of fish, either as the target or bycatch of routine fishing for human consumption.

5.2.1 Fish

In the marine environment, microplastic uptake has been seen in fish throughout the trophic levels; however, the level of plastic observed varies even in species with similar feeding modes. In the Mediterranean, ingestion of microplastics has been recorded in bycaught blackmouth catsharks, *Galeus melastomus*, [54], 68% of Bogue (*Boops boops*) [55], 15.3% of dogfish, *Scyliorhinus canicular*, 16.7% of hakes, *Merluccius merluccius*, and 18.8% of red mullets, *Mullus barbatus* [56].

In the North Sea, examination of seven common species (1203 individuals) revealed plastic particles in just 2.6% of the examined fish (five of the seven species). The abundance of contaminated individuals and the number of items recovered varied with species and location; 5.4% in the southern North Sea and 1.2% in the northern North Sea [57]. Demersal species (cod, dab, and flounder) and pelagic fish species (herring and mackerel) from the North and Baltic Sea have also been examined for the presence of microplastic. Of the 290 individuals, plastics were observed in 5.5%; 74% of these plastic particles could be classed as microplastic (<5mm). In this case, just 3.4% of the demersal species

contained plastics, compared to 10.7% of the pelagic individuals [58]. In the English Channel, 504 fish from 10 species were examined for the presence of microplastic. Examination of the gastrointestinal tracts indicate plastic uptake in 36.5% of individuals, all five pelagic species and all five demersal species had ingested plastic (1.90 per fish) with no significant difference between the two groups [59].

Analysis of Japanese anchovy (*Engraulis japonicus*) sampled in Tokyo Bay revealed microplastic retained in the intestinal tracts of 49 out of 64 fish (77%). Fish contained an average of 2.3 pieces of plastic, with up to 15 pieces per individual. Unlike other studies, the majority of plastics recovered from anchovy were fragments (86.0%), followed by beads (7.3%) [60]. In offshore habitats, dissection of 761 mesopelagic fish that undergo daily vertical migrations (following the diel migration of planktonic prey) from the Northeast Atlantic. Analysis indicates revealed microplastic contamination in 11% of the sampled fish. There was no significant difference in the abundance or frequency of plastic ingestion between species, sampling location, or migration behavior [61].

As with invertebrates, the number of species from brackish and freshwater environments that are known to ingest microplastic is increasing. Twelve percent of gudgeons from French rivers have been seen to contain plastic [62] as were 20% of Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*) from the African great lakes. Uptake in species from the great lakes was suggested to be the result of urban waste and consumer plastic use [63]. In the Brazos River Basin, United States, ingestion of microplastic and synthetic fibers was observed in bluegill (*Lepomis macrochirus*) and longear (*Lepomis megalotis*) sunfish (Centrarchidae) [64]. Of the 436 sunfish examined, 196 (45%) stomachs contained microplastics. As with the Great Lakes study, the abundance of recovered microplastics was highest in urban sites, followed by downstream and upstream sites [64].

5.2.2 Birds

Aquatic birds from both fresh and salt water environments have been seen to contain microplastics within the gut. In wading birds such as the phalarope and surface feeders such as fulmar it may be that plastics are selectively consumed as they resemble fish eggs or other natural food, whereas predatory species may be exposed to plastics via contaminated prey.

In Canada, a study of birds utilizing freshwater habitats revealed the 15 of the 350 birds examined contained plastic; accounting for eight of the 18 studied species [65]. In the marine environment, dead or stranded pelagic feeding procelliformes, tube nosed seabirds, revealed microplastic in 89.5% of northern fulmars (*Fulmarus glacialis*) (see Fig. 21.5) and 64% of sooty shearwaters (*Ardenna grisea*). Average plastic loads were 19.5 pieces and 0.461 g for fulmars and 13.3 pieces and 0.335 g for shearwaters.

Stranded individuals were initially recovered for rehabilitation. In the 33 individuals that could not be successfully rehabilitated, there was no significant reduction in pieces or mass of plastic. Successful rehabilitation occurred in three individuals, these were successful in regurgitating plastics, which suggests that a proportion may be eliminated from the intestinal tract [66]. In a similar study, seven red phalaropes (*Phalaropus fulicarius*), six were seen to contain plastic particles in their intestinal tract. Comparison between plastic abundance and fat reserves indicates a negative impact on nutritional state [67]. Analysis of 92 pellets regurgitated by Great Cormorant (*Phalacrocorax carbo*) revealed 3.2% occurrence of plastic items. [68].

Examination of the gut content of 12 bird species commonly feeding in terrestrial habitats revealed microplastic uptake in 16 of 17 individuals. In total, 364 items of anthropogenic litter



FIG. 21.5 Fulmar (*Fulmarus glacialis*).

were recovered from species from top carnivores to lower tier omnivores, including: common buzzard (*Buteo buteo*); black kite (*Milvus migrans lineatus*), common kestrel (*Falco tinnunculus*), large hawk-cuckoo (*Cuculus sparveroides*), cattle egret (*Bubulcus ibis*); little grebe (*Tachybaptus ruficollis*), dunlin (*Calidris alpina*); common sandpiper (*Actitis hypoleucos*); eye-browed thrush (*Turdus obscurus*), gray-backed thrush (*Turdus hortulorum*), common magpie (*Pica pica*), and spotted dove (*Streptopelia chinensis*). Of these items, plastic fibers represented 54.9% (200 items) and plastic fragments represented 7.7% (28 items) of total litter items [69].

5.2.3 Mammals

The largest organisms known to ingest microplastics are represented by marine mammals. Understandable, identification of microplastics in the digestive tracts of large cetaceans presents numerous challenges to the researcher. Nevertheless, Stranded True's beaked whale, *Mesoplodon mirus*, suspected to be feeding on mesopelagic fish have been identified as consuming microplastics [70]; and, filter feeding humpback whales, *M. mirus*, were seen to consume a range of plastic types including fragments and threads (1 mm–17 cm) [71]. In their 2017 review of debris in cetacean species bycaught or stranded in Irish waters, Lusher et al., observe microplastic contamination in porpoises, dolphins, and toothed whales [72].

Microplastic ingestion in smaller marine mammals such as pinnipeds, seals, sea lions, and walruses, and can be determined by evidence left at regular colonies. Scat samples of fur seals (*Arctocephalus* spp.) on Macquarie Island revealed 164 plastic particles with a mean length of 4.1 mm, most of which were formed from the fragmentation of larger plastics. The authors propose that these particles were accumulated from the consumption of contaminated pelagic prey, primarily *Electrona subaspera* [73].

5.3 Implications for Animal Health

There are numerous potential outcomes to interactions between biota and microplastics; however, the number of available papers is currently limited. Following ingestion, plastics may be egested or excreted with other wastes or they may accumulate within the digestive tract, other organs, or tissues. Microplastics taken up during ventilation could be depurated in clean conditions or remain adhered to respiratory structures. During the exposure period, plastics have the potential to either affect the health or functioning of the organism, or to remain inert until expelled or the host organism dies of an unrelated cause (following which the plastic would return to the environment).

One of the most commonly recognized impacts of plastic uptake is reduced feeding efficiency, previously observed in interactions between macroplastic and marine fauna, including birds and turtles. Feeding may be limited by reduced appetite, caused by aggregations of plastic in the gut; referred to as false satiation. Alternatively, damage or impairment of the feeding appendages or the gastrointestinal tract may result in reduced uptake or assimilation of food, resulting in nutrient dilution.

Damage to the gastrointestinal tract and digestive organisms has been noted in both invertebrates and vertebrates. Laboratory observation of *M. edulis* has indicated that polyethylene particles may be taken up into the gills or ingested and taken up into the digestive gland, resulting in inflammation and lysosomal membrane destabilization [74]. Similarly, European sea bass, *Dicentrarchus labrax*, fed "clean" polyvinyl chloride (PVC) pellets demonstrated severe histological changes to the intestine. It is suggested that the degree of damage observed may completely reduce intestinal functions [75]. Zebrafish, *Danio rerio*, exposed to polystyrene microspheres have also displayed the uptake of plastics into the gills, gut, and liver. Histopathological analysis showed that microspheres

in the liver resulted in inflammation and lipid accumulation, significantly increased levels of superoxide dismutase and catalase activity, and altered lipid and energy metabolism [76].

Functional impairment of feeding has been reported in the copepod *Centropages typicus* in which algal feeding rates declined following the consumption of microplastics ($>4000\text{ mL}^{-1}$) [41]. Another, larger, crustacean—*Gammarus fos-sarum*—is known to ingest both fibers and spheres. Despite being seen to egest both forms of plastic, fibers were seen to negatively affect food assimilation [47]. *N. norvegicus* exposed to plastic fibers over 8 months were seen to have lower nutritional states [77].

In the marine annelid, *Arenicola marina* microplastic uptake resulted in increased gut residence time, reduced energy reserves [78], the production of fewer casts, and higher metabolic rates [79]. Reductions in feeding and energy reserves may result in increased mortality, as observed in the earthworm, *Lumbricus terrestris*; significantly increased mortality and decreased energy reserves were observed at 28%, 45%, and 60% exposure, when compared to 7% and the control (0%) [46].

In fish, ingestion of microplastics by juvenile *Pomatoschistus microps* was linked to reduction of the predatory performance (65%) and efficiency (up to 50%) in fish from the Lima estuary; however, this was not seen in Minho estuary fish [80]. Plastic uptake may also reduce mobility as observed in the beachhopper, *Platorchestia smithi*. Here ingestion was linked to reduced mobility (jumping ability) and survivorship in [81].

As well as affecting feeding efficiency, interactions between microplastic and biota may also affect fecundity. Reductions in reproductive success have been observed in oysters (*Crassostrea gigas*) [82]; however, European flat oysters (*Ostrea edulis*) revealed no significant negative impacts, while their associated faunal assemblages demonstrated a range of effects including lower biomass of *Scrobicularia plana*

and reduced abundance of juvenile *Littorina* sp. and *Idotea balthica* [83].

In addition to physical damage and impairment, adsorbed hydrophobic contaminants and additives may also be transferred from microplastic to organisms. The potential for chemicals to move from plastic to the organisms is dependent on relative partitioning and external conditions. Such interactions have been indicated in fish fed plastic presorbed with chemical pollutants from the marine environment. Here test subjects were seen to accumulate pollutants, resulting in apparent toxicological effects. Less significant impacts were also seen in fish fed “clean” plastic [84].

Less studied is the potential for microplastics to form a route for the redistribution of species. Microplastics have been seen to transport microorganisms, microbes, and bacterial communities. Analysis of bacterial populations on plastics from rivers feeding the Laurentian Great Lakes indicates that bacterial assemblages on plastic are less diverse than those of natural debris. The common colonizers included plastic decomposing organisms and pathogens [85]. In the marine pelagic zones microplastic colonizers have been seen to include diatoms, “epiplastic” coccolithophores, bryozoans, barnacles, dinoflagellates, isopods, and a marine worm, as well as rounded, elongated, and spiral cells putatively identified as bacteria, cyanobacteria, and fungi [86]. Plastics have also been seen to transport invasive and potentially harmful species including the coral pathogen *Halofolliculina* spp. [87].

While a growing number of studies report observations of negative impacts resulting from interactions with microplastic, there are also many that reveal no significant effects. Larval European flat oysters (*O. edulis*) which ingested biodegradable and conventional microplastics over 60 days demonstrated no significant impacts on health or survivorship [83], and ingestion of polystyrene particles by Pacific oyster (*C. gigas*) larvae resulted in no significant change in feeding or growth [88].

In crustaceans, *Idotea emarginata* were seen to unselectively ingest microspheres, which were subsequently seen throughout the gastrointestinal tract. However, plastics in the feces were recorded at the same concentration of the initial feedstock, indicating that plastics may be readily egested. Exposure to plastic over 6 weeks revealed no significant effects of microplastic ingestion on mortality, growth, and intermolt duration [89]. Similarly, *Echinogammarus marinus* fed up to 99 microplastics g⁻¹ for 35 days were seen to exhibit no retention of plastic and no significant impacts on feeding or growth [90]. In fish, larval sea bass exposed to polyethylene microbeads between 7 and 43 days post-hatching demonstrated only a limited increase in mortality with increased microbead abundance, and an increase in cytochrome-P450-1A1 (*cyp1a1*) expression positively correlated with the number of microbeads [91].

Despite the high level of concern regarding the potential for microplastics to transport contaminants, some studies of chemical transfer have reported no negative impacts. Several models have indicated that the transfer of persistent organic pollutants from plastic to the host organism will be negligible when compared to the continual exposure to these pollutants in solution [92]. In common goby (*P. microps*) the presence of microplastics was seen to delay pyrene-induced fish mortality and was related to an increase in pyrene metabolites, indicating that the presence of microspheres changes the bioavailability or biotransformation of pyrene [93]. In Northern Fulmar (*F. glacialis*) from Norwegian waters concentrations of persistent organic pollutants in the liver were not significantly increased in the presence of medium or high plastic loads. [94].

In the environment, the degree of damage caused by interactions between microplastic and biota will be determined by the concentration of microplastic and duration over which the organism is exposed. In highly contaminated areas, some individuals may take in numerous

successive particles resulting in extended exposure, but not retain any; whereas others may take in very few items, but hold them in the gut or tissues over the same period due to the shape of the plastic or their individual morphology. Organisms with comparatively simple guts, such as annelid worms, should have limited trouble in excreting ingested plastic with typical food stuff. This has been observed in the rate of expulsion of microplastic by oysters [83, 88]. Conversely, comparatively complex digestive tracts have both pinch points and hard points at which plastics may become lodged, such as that of *N. norvegicus*, may result in extended microplastic retention [49].

From the available data, it is currently not clear whether long-term retention or high concentrations of microplastic are more detrimental to an organism, and long-term impacts may depend upon an animal's ability to migrate to areas of lower contamination. It is not possible to compare many of the current studies due to the disparity in the reported conditions, and standardization is essential to assess the relative threat of microplastic to individual taxa. Standardization of plastic form and dosage and comparison between the key taxa are now essential in clarifying our currently patchy knowledge of microplastic effects (see Fig. 21.6).

5.4 Microplastic-Human Interactions

According to the FAO 17% of human dietary protein comes from marine and freshwater sources [95]. Perhaps unsurprisingly, many of the marine species identified as containing microplastics are regularly consumed by humans. Gut content analysis carried out on 263 individuals from 26 commercially harvested fish species from Portuguese waters revealed microplastic contamination in 17 species (19.8% of the sampled fish); of the fish which contained microplastic, 63.5% were benthic and 36.5% were pelagic species [96]. Similar contamination rates were observed in fish sampled

Ingestion

- Histological changes
- Nutrient dilution
- False satiation
- Translocation
- Altered enzymatic activity
- Reduced nutritional state
- Reduced reproductive success
- Increased mortality

Respiratory interaction

- Histological changes
- Translocation
- Respiratory impairment

Physical interaction

- Adherence to appendages
- Reduced movement and feeding efficiency
- Confusion effects e.g., nonselective feeding

Chemical transfer

- Altered pollutant loads

FIG. 21.6 Summary of the major effects related to microplastic contamination.

from markets in Indonesia and the United States, with microplastic contamination in 25%–28% of the fish sampled, representing 55% and 67% of the species identified [97]. An assessment of two fish species caught off Brazil's east coast indicated that 63% of *Scomberomorus cavalla* and 33% of *Rhizoprionodon lalandii* were contaminated by plastic pellets [98].

Commercially harvested shellfish have also been seen to contain microplastic. In their study of animals in Indonesian and American fish markets, Rochman et al. [97] revealed microplastic contamination in 33% of the sampled individuals [97]. In a similar study, analysis of commercially available *M. edulis* and *C. gigas* revealed the presence of 0.36 ± 0.07 particles g^{-1} in *M. edulis* and 0.47 ± 0.16 particles g^{-1} in *C. gigas*. It was calculated that the human exposure from shellfish may amount to 11,000 particles annually [99].

It is not only microplastic contamination in our food that we need to be aware of. In addition

to various species for human consumption, microplastics have also been observed in both bottled and tap water, honey, sugar [100] and, in one alarming study, 24 varieties of German beer, in which 2–79 fibers, 12–109 fragments and between 2 and 66 granules were identified per liter [101]. Despite these observations, the potential impact on human health remains to be explored.

6 REDUCING AND RECOVERING MICROPLASTIC

As with the science exploring the distribution and impacts of microplastics, the control of both primary and secondary microplastics is relatively unexplored. Many methods of reducing the proliferation of microplastics to the environment are either underdevelopment or in their first years of implementation, and there is little information to confirm their effectiveness. A key target in the reduction of microplastics intrinsically linked the mishandling and loss of large plastic parent material. To date, the reduction of large plastic debris from commercial and domestic sources entering solid waste has focused on the reduction and elimination of single use plastics. The most advanced of these efforts are those aimed at reducing the circulation of plastic carrier bags, with around 50 countries and territories imposing levies on single use bags. Many also prescribe a minimum film thickness for reusable bags sold in their place. The global effectiveness of these schemes has yet to be confirmed; however, on *****UK beaches, where a five pence plastic levy has been enforced since October 2015, participants in the Marine Conservation Society's Beach Watch reported almost 50% fewer bags in 2016 than in 2015 [102].

In addition to the reduction in plastic bags, municipalities and institutions in Australia, India, and the United States have implemented local bans on the sale of bottled water. While

there is currently limited evidence as to their efficacy, the ban on plastic bottles in the United States national parks is believed to have resulted in an annual reduction of 2 million bottles. A contrasting approach is the reintroduction of reusable containers; deposit schemes have been proposed, designed to encourage the reuse and return of bottles by the public. Detractors from this approach suggest that the necessary space and behavioral changes required for these schemes are too great for their long-term success.

For macroplastics in the environment, floating litter collectors in both riverine and marine habits may be employed as passive recovery devices. Local currents herd plastics into aggregation points or suspended nets which are periodically emptied (Fig. 21.7). Before deployment in coastal waters, patterns of water movement should be used to highlight the most effective placement of collectors [103]. The resulting plastics are then redirected to traditional sorting facilities. A similar, although more active method, is the “Fishing for Litter” concept. Commercial trawlers are encouraged to bring

ashore plastics brought up with fishing gear. Although this method has been seen to be effective in a number of locations, numerous vessel owners report prohibitive charges for waste disposal, leveled by local port authorities. Anecdotal evidence of similar issues is reported by local beach clean groups. Volunteer beach cleans and local litter picks are globally important in both removing and reporting marine litter. The Marine Conservation Society’s annual beach cleans have gathered data on beach litter since 1994, and the presence of fragmented plastics and primary microplastic is highlighted to both participants and readers of the resultant reports. More focused is the Great Nurdle Hunt, organized by Fidra. Primarily based in the industrially impacted Firth of Forth, the survey asks members of the public to record the number of nurdles (preproduction plastic pellets) found on beaches. The availability of facilities to receive and transport collected litter varies greatly with location. Authorities wishing to enable recovery of plastic from aquatic habitats should place great emphasis on onshore disposal of plastic recovered by both of passive and active litter collection.

The current approaches to reducing macroplastic parent materials in terrestrial environment have focused on the reduction of single use plastics handled by the consumer. The current control of microplastic entering wastewater is more general and has focused on primary and secondary microplastics from both industrial and domestic sources. Collaboration between NGOs and plastics manufacturers has resulted in the implementation of Operation Clean Sweep, which reduces the release of nurdles through the best practices in handling and transport. Evidence of pellet distribution and abundance in the marine environment provided by citizen scientists participating in the Great Nurdle Hunt has resulted in increasing engagement from industry, with 70 organizations in 37 countries currently committed. Another primary microplastic source, that of microbeads in

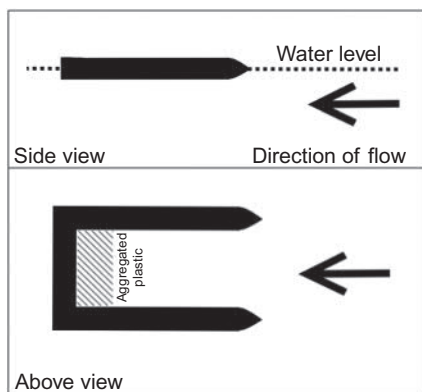


FIG. 21.7 A floating plastic collector for use in river environments. The horseshoe shaped collector is anchored to a buoy, allowing it to orientate itself in the flow. The body of the collector floats slightly above the water level and extends to a depth of 50cm or more. Plastic litter is carried into the mouth of the collector by the flowing water, aggregating in the hatched area indicated.

personal care products, has been targeted for stronger, legislative action. In the United States and United Kingdom, public outcry and governmental inquiry have resulted in a ban on the sale of products containing microbeads. The Netherlands, Ireland, and Canada have also conducted examinations of the impacts of microbeads, with varying levels of pressure being put on manufacturers to reduce the number and sale of products which contain the beads.

Sources of secondary microplastics in wastewater, such as fibers released from clothes washing, are less easily controlled. There have been a number of developments in the retention of microfibers released during domestic clothes washing. Products have been designed to gather fibers before they exit the washing machine drum. Garment bags, such as the GuppyFriend, allow the movement of detergents while retaining fibers released. Following the wash, the bag is inverted and scraped to remove microfibers formed. Another method of fiber catching is demonstrated by the newly released Coraball, modeled on filtering corals; the branching arms of the ball trap fibers which are removed following the wash cycle. While these methods may be effective in reducing the number of fibers released, there is no method in place for the collection and management of this new resource.

The removal of suspended microplastics by water treatment works has recently been examined. The treatment process has been seen to significantly reduce the suspended plastic load [18, 104]; however, the proportion removed is highly dependent on the treatment processes of the plant. Observations of suspended microplastics between treatment phases have revealed that membrane bioreactors are the most efficient stage, removing up to 99.9% of microplastics, followed by rapid sand filters (97%), dissolved air floatation (95%), and disc filters (40%–98.5%) [105]. A similar study has revealed that primary treatment and

flocculation alone may remove around 78% of suspended microplastics [18].

Despite the efficacy of this procedure, estimates of daily microplastic released from secondary treatment still reach between 8.1×10^6 [106] and 65×10^6 [18] microplastics per day. In addition, the proportion of plastic removed may result in highly contaminated sludges, the analysis of which has previously revealed concentrations between 4196 and 15,385 particles kg^{-1} (dry weight) [17]. This raises questions regarding the treatment and spreading of sewage sludge on farmland, and the potential for further distribution and resulting runoff to water courses [16].

7 CONCLUSIONS

Over the past 50 years, mass production and population growth have resulted in the proliferation of microplastics, both as commercial products and the degradation of larger plastic materials. Despite having only been recognized as an environmental issue in 2004, microplastic pollution has quickly become a topic of both scientific and public concern. As populations continue to rise, the pool of microplastic sources will also grow. As a result, the diverse sources and unique properties of primary and secondary microplastics will place challenges on an underprepared waste infrastructure. In addition to reducing or replacing primary microplastics and the large plastics from which secondary microplastics are formed, the release of microplastic fibers, tire fragments, and abrasives must also be addressed. Solutions must be developed to key challenges in order to manage the microplastic outputs of a growing global population, including how we recover greater proportions of microplastic in waste water, and what to do with this new resource.

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Marine Plastic Pollution: Other Than Microplastic

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1 INTRODUCTION

The human race generates a considerable amount of solid waste on a daily basis. Global quantities of this waste are increasing, although amounts vary between countries. Plastics are a major component of this waste, as well as

being the dominant category of litter reported in the marine environment. There has been growing evidence about the effects plastic contamination can on the environments. Plastic litter now contaminates marine habitats from shallow water to the deep sea and has been identified as a major global issue by the United

Nations Environment Assembly and in the G7 Leader's declaration 2015 [1–3].

Plastics are synthetic or semisynthetic organic polymers that are typically lightweight, strong, inexpensive, durable, and corrosion resistant [4, 5]. Most plastic items are composed of hydrocarbons derived from fossil oil or gas feedstocks [6]. During the conversion from resin to product, a wide variety of additives (such as fillers, plasticizers, flame retardants, thermal stabilizers, antimicrobial agents, and colorings) may be added to enhance performance and appearance [7]. As a consequence, plastic materials can take many forms including rigid items together with more flexible films, adhesives, foams, and fibers. The most commonly used polymers are high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET), which cumulatively account for approximately 90% of total plastic production [8].

These plastic materials can be made into a vast range of products that bring numerous societal benefits, especially in healthcare, agriculture, transport, construction, and packaging [9]. The versatility of plastic materials has resulted in a substantial increase in their use from 5×10^6 t (5 million tonnes) globally in the 1950s to over 300×10^6 t today [7, 8].

Some applications of plastics have a long service life, such as PVC and PP components used in vehicles or the construction industry [10]. Despite the durability of plastics, the main use is in relatively short-lived and single-use applications, such as packaging. These applications account for around 40% of all plastic production. While packaging can help protect food, drink, and other items (thus reducing damage and wastage of products), it also results in rapid accumulation of persistent plastic waste. These items are frequently made of PE or PET and represent a substantial proportion of waste managed via landfill, incineration, and recycling [11]. This has led to the most abundant types

of litter found within the marine environment being single-use items, together with rope and netting [12]. Plastic represents a substantial fraction of municipal waste overall and can subsequently enter the marine environment from a variety of different sources.

It is estimated that 75% of all marine litter is plastic and this debris has been widely reported in the environment; accumulating at the sea surface [13], on shorelines of even the most remote islands [14], in the deep sea [15, 16], and in arctic sea ice [11, 17]. There is also increasing awareness of the accumulation of plastic litter on land as well as in freshwater habitats [18, 19].

Although there is uncertainty about the absolute quantities of plastic in the environment, or the ultimate sinks for this debris, there is evidence of increasing quantities over time [11, 20]. Fragmentation of larger items of litter has subsequently resulted in accumulation of smaller plastic pieces including microplastics [11]. The accumulation of plastic litter presents a range of negative economic and environmental consequences [1]. While the focus in this chapter is on plastic in the marine environment, freshwater habitats are also contaminated and rivers provide major pathways of plastics to the ocean [18].

2 THE DEGRADATION OF PLASTIC AND SIZE CLASSIFICATIONS

Plastic debris can be defined and described in a variety of ways including by shape, color, polymer type, origin, and original usage (e.g., packaging). Plastics also enter the aquatic environment in a wide range of sizes [21, 22] and have been reported hundreds of meters in length to microns in diameter. There are three categories that are typically used to describe the category of plastic according to its size: macroplastic (>20 mm diameter), mesoplastic (5–20 mm), and microplastic (<5 mm) [11, 23].

2.1 Macro and Mesoplastic

Macroplastic typically refers to items larger than 20 mm, and mesoplastic refers to items larger than 5 mm but smaller than 20 mm. However, sometimes there can be a crossover of dimensions as they have been used differently in various studies. Due to the high visibility of plastic and its contamination in the environment, macroplastic may be perceived as one of the most concerning forms of plastic pollution.

The accumulation of macroplastic has been reported in a wide range of habitats [24, 25]. Many cleanup campaigns typically focus on these larger items, but there is wide geographical variability in abundance, which makes it difficult to analyze potential trends. However, due to the size of this debris, it is often possible to categorize items according to their original usage; for example, packaging, fishing, or sewage-related debris.

2.2 Microplastic

Microplastic is used as a collective term to describe a heterogeneous range of small plastic particles and fibers <5 mm in length. Microplastic can then be further divided into categories based on their origin: primary and secondary microplastics. Particles that directly enter the environment in the microplastic size (<5 mm in diameter) are described as primary microplastics. Secondary microplastics are those formed in the environment from the fragmentation of larger items of plastic debris [22, 26]. Microplastics are discussed further in Chapter 21.

2.3 Degradation and Size Change

Plastics are generally resistant to degradation and estimates for the complete degradation of plastic debris in the environment range from decades to centuries [27]. Plastics can break-down in size due to fragmentation leading to smaller and smaller particles, including

microplastics (discussed in Chapter 21) [11, 28]. As a consequence, macro-mesoplastic is a major secondary source of microplastic.

Degradation and fragmentation of plastic can occur when they are exposed to ultraviolet radiation (sunlight). This process is called photooxidation and is a result of the absorbance of high-energy wavelengths of the ultraviolet (UV) spectrum by the polymers [29]. Once degradation is initiated, it can proceed through temperature-dependent thermo-oxidative reactions without further exposure to UV radiation, as long as oxygen is available [30]. This ultimately causes plastics to become brittle and fragment, especially if exposed to physical action.

The timescale for degradation of discarded plastics is not known with certainty and will depend on the chemical nature of the material, the characteristics of the environment in which they persist, and the manner in which degradation is measured [7]. A range of factors influence rates of degradation in the environment; hydrolysis and biodegradation occur at rates several orders of magnitude slower than the oxidative mechanisms [30]. Plastics typically take much longer to degrade in water than they do on land, mainly owing to the reduced UV exposure and lower temperatures found in aquatic habitats [31]. It has been suggested that all of the conventional plastic that has ever been produced, with the exception of any material that has been incinerated, still persists in the environment in a form too large to be biodegraded [32].

3 SOURCES, TRENDS, AND ABUNDANCE ESTIMATES

Marine litter is human-created waste that has been deliberately discarded, unintentionally lost or transported by wind and rivers into the sea and on beaches.

Sources of litter, of which plastic is the largest component, can be characterized in several

ways [33]. The most common method is to classify marine litter sources as either land based or ocean based, depending on where the litter entered the sea. Land-based sources include litter from the general public, industry, harbors, recreational use of the coast, and unprotected landfills. Ocean-based sources of marine litter include shipping, fishing, and off-shore installations such as platforms, rigs, and aquaculture sites.

3.1 Land-Based Sources

It is widely cited that 80% of marine litter originates from land, with densely populated or industrialized areas being the major sources [4, 34]. However, there is little empirical data to confirm this estimate. It has been estimated that on a global scale, the input of plastic into the oceans from land-based sources is in the region of $6.4 \times 10^6 \text{ t year}^{-1}$ [35]. This plastic litter can be transported to the oceans by wind, municipal wastewater, and freshwater systems [22, 36]. For macroplastics, transport by wind to the oceans may be significant, especially since approximately 50% of the human population live within 80 km of the sea [37].

Waste management frameworks, which are designed to help minimize the loss of litter to the environment, can also contribute to the problem. This can result from windblown litter escaping into the wider environment [11, 38, 39]. In industrialized countries, waste that is deposited in landfills is usually covered regularly with soil or a synthetic material, and the landfill is cordoned by a fence to prevent any debris accidentally leaving. However, in developing regions this is often not the case [11, 40]. The residues from plastic recycling could also unintentionally escape into the environment [37]. Furthermore, assuming there are no improvements in waste management infrastructure, the cumulative quantity of plastic waste available to enter the marine environment from land could increase by approximately three times over the next decade [35].

Additionally, human activity on the coast can create direct inputs of marine debris. Coastal tourism, recreational and commercial fishing, marine vessels, and marine industries (e.g., aquaculture, oil rigs) are typical examples. Tourism and recreational activities account for an array of plastics being discarded at beaches and coastal resorts [4]. In 2002, 58% of the debris collected in the International Coastal Cleanup was attributed to shoreline and recreational activities [41]. Work in the Northern area of the South China Sea also found that the majority of floating and beached plastic debris originated from coastal recreational activities and land-based sources [42].

Unintentional loss of macroplastic products while in-service can also occur when catastrophic events, such as tsunamis, hurricanes, or floods, carry large amounts of material of all kinds into the marine environment [43]. Moreover, sewage overflows can have accidental loss into the marine environment and extreme events can compound this issue. [44, 45].

3.2 Ocean-Based Sources

Items released at sea are also an important component; analysis of floating macro-debris revealed that 20% by number and 70% by weight was fishing related, principally floats and buoys [46]. This was based on 4291 visual observations from 891 sampling locations in the North and South Pacific, North and South Atlantic, Indian Ocean, Bay of Bengal, Mediterranean Sea, and coastal waters of Australia.

Studies have indicated a significant relationship between the number of ocean-based plastic items found on beaches and the level of commercial fishing activity [47, 48]. In 2010 the amount of fishing gear lost to the environment was estimated at around $640,000 \text{ t year}^{-1}$ [49]. Discarded fishing items, which include monofilament lines and nylon netting, can float at a variety of depths and result in “ghost fishing” and entanglement of aquatic organisms; this will be discussed in the “impact” section [49].

3.3 Trends and Abundance Estimates

The sources of marine plastic litter are mostly well known, but there is still a considerable lack of knowledge concerning the relative importance of the different sources and their original usage [50]. Some items can be attributed with a high level of confidence to their origin, such as fishing gear and sewage-related debris [44]. However, some types of plastic debris are much harder to trace back, such as microplastic fragments.

Given the large amount of macroplastics entering the environment, it is generally assumed that there will be a rise in microplastics from the fragmentation of larger items [30]. However, the fragmentation rates of macroplastics are largely unknown, and as a result little quantitative information is available on the relative contribution from the fragmentation of larger items to the abundance of microplastics [26, 51, 52]. Therefore it is important to understand sources, pathways, and quantities

of larger items to the environment as they are the most likely source of microplastic in our oceans [21, 27, 30].

In terms of abundance, there are no definitive estimates of the total quantity of plastic in the environment overall. Estimates based on counts at sea suggest between 7000 and >250,000 t of plastic are now present in the open ocean surface [46, 53]. The trends of production, consumer use, and demographics all point to a further increase of plastic use in the future [54, 55]. Hence there are considerable concerns that the problems of plastic pollution will escalate unless disposal practices change.

4 DISTRIBUTION

Once released into the marine environment, and due to their durability, plastic debris has the potential to become widely dispersed (Fig. 22.1). The distribution of plastic debris

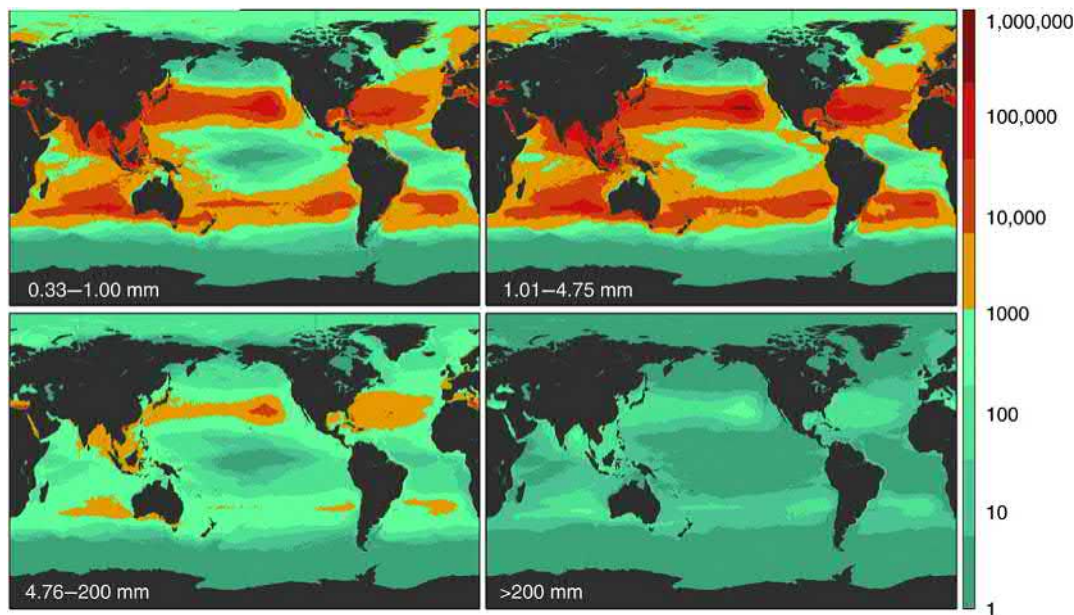


FIG. 22.1 Plastic contamination in the oceans. A model result for a global count density in four size classes of plastic. The combined data from 24 sampling missions with oceanographic computer modeling, the global distribution of plastic particles was predicted in specific size classes. Macroplastic is considered >5mm, so is displayed by the bottom two tiles [46].

can be transported by wind and currents [25,56]. Plastic has been found to accumulate in the oceans [20], estuaries [57], and even in remote habitats such as in arctic ice [17]. Within these environments, plastic debris of all sizes has been reported at the sea surface [53], suspended in the water column [58], sediments (including those in the deep sea) [15, 59, 60], and beaches [12].

Macroplastic has spread to unhabituated areas, such as Antarctica, where research by Barnes et al. [61] found a plastic cup and two fishing buoys in the Dumont D'Urville and Davis seas, as well as two pieces of plastic packaging and a fishing buoy in the Amundsen Sea [61]. Plastic debris has also been found in freshwater environments showing that this issue is not limited to the marine environment [62–64].

4.1 Floating and Suspended Plastic Debris

Floating debris can be transported by wind and currents at the sea surface but may eventually sink to the seafloor, be deposited on the shore, or degrade over time [65]. Hence, the sources of floating marine debris in the oceans can be difficult to identify, given the persistence and potential for long-range transport of light-weight buoyant materials [25].

Floating macrolitter, which includes plastics, is typically monitored by visual observation from ships. Visual sightings of macroplastics from ship-based observers have been reported since the 1970s [66] and have proved to provide useful information about litter densities and how these compare between regions and over time. An example being in 2009; research from Titmus and Hyrenbach [67] observed the surface water from the American west coast to the North Pacific subtropical gyre and back to the coast [67]. This provided data during 74 h of observation corresponding to a transect length of 1343 km. A single observer at 10 m above sea level recorded a total of 3868 pieces, of which 90% were fragments and 96% of these were

plastic. Eighty-one percent of the items had a size of 2–10 cm, 14% of 10–30 cm, and 5% of >30 cm. Their research found that the abundance of debris increased toward the center of the gyre.

Visual observations from vessels are constrained by an inability to detect smaller fragments (<20 mm) and to retrieve the observed items for further analysis [67]. There has been an effort to standardize the observational methods used in order to reduce potential bias in the data. Factors such as sea state, elevation of the observation position, and ship speed can all contribute to variations in the number of items measured [68]. A simple methodology has been proposed that should greatly improve the robustness of observations, allowing a more coherent picture for the distribution of floating plastic objects [69]. This takes into account the minimum size of items counted, the distance of items from the ship, the height of the observer above sea level, and the position of the observer relative to the ship's bow wave.

Aircraft and satellite observations may also prove useful; for example, in the aftermath of natural disasters, such as the 2011 Tōhoku earthquake tsunami in the North Pacific [70]. Looking to the future, automatized approaches using digital imaging and image recognition techniques for the autonomous large-scale monitoring of plastic litter are being researched [71].

4.2 Plastic Debris on the Seafloor

Plastic items that are a range of sizes are commonly observed, or collected, from the seafloor [33]. Their ability to sink through the water column to the sea floor is determined by the plastics composition and environmental conditions [44]. Polymers denser than seawater (e.g., PVC) will sink, while those with lower density (e.g., PE and PP) will tend to float in water column. Biofouling of organisms on the plastic surface increases the weight of plastic objects, thus increasing the potential for them to sink [72, 73].

Degradation, fragmentation, and the leaching of additives can also influence the density of objects and hence their distribution in the water column [74]. As a result, plastic can dominate macro-debris on the sea floor.

Sea bed surveys of macro-debris have been conducted with divers [75, 76], trawl surveys [77–79], and submersibles/remote-operated vehicles [80]. The accumulation of large plastic items has also been found on the sea floor in the deep sea, where research by Galgani et al. [81] found that plastic bags accounted for >70% of total debris off the French Mediterranean coast. The amount of plastic litter is so great in some areas that initiatives have been started to clean the seabed with trawls, despite concerns about the ecological impacts of trawling [82].

The geographic distribution of debris on the ocean floor is strongly influenced by

hydrodynamics, geomorphology, and human factors [33, 81]. Moreover, there are notable temporal variations, particularly seasonal, with tendencies for accumulation and concentration of marine litter in particular geographic areas [83]. The fragmentation and degradation of plastics at depth is unknown, but accumulation of debris on the seafloor certainly began before scientific investigations started in the 1990s [44].

4.3 Plastic Debris on Beaches

The majority of studies on marine plastic debris have focused on its occurrence in coastal waters and open ocean areas. However, plastic debris is now evident on beaches globally (Fig. 22.2). Researching macro-debris on beaches uses different approaches that sometimes lack



FIG. 22.2 A beach clean organized by the Marine Conservation Society, United Kingdom. *Courtesy of Jack Holt.*

detail [84]. These studies typically range from a local [42] to a regional scale [85] and cover a broad temporal range. Information on sources, composition, amounts, usages, baseline data, and environmental significance are often also gathered [12, 86, 87].

The majority of studies investigating the abundance and distribution of plastic debris on beaches have used citizen science-based data [19, 88]. An example being research from Nelms et al. [12]; this research collected data over a decade (2005–14 inclusive) using results from Marine Conservation Society (MCS) volunteers during beach litter surveys in the United Kingdom. Their results found that plastic was the main constituent of anthropogenic litter and the majority of traceable items originated from land-based sources. However, over the 10-year time there was no statistically significant change in the total quantity of litter detected [12].

Factors influencing the accumulation of this debris in coastal areas include the shape of the beach, location, and the nature of debris [89]. Additionally, the abundance of stranded and drifting plastic debris (both macro and micro particles) along beaches and coastal areas is expected to increase with projected increases in sea level, wind speed, wave height, and altered rainfall conditions [40].

5 IMPACTS

There is a reasonably extensive evidence base relating to the impacts caused by plastic litter in the marine environment. This includes direct physical impacts on marine wildlife and humans, as well as effects on habitats—both on land and at sea.

5.1 Impacts on Marine Life

Over 700 species of marine organisms have been reported to encounter plastic debris, which can result in severe physical harm or death, or

more subtle effects on behavior and ecological interactions (e.g., the ability to escape from predators or migrate) [90]. The majority of documented accounts relate to entanglement and ingestion [90–92]. It is likely that there are also a range of sublethal effects that have not yet been recognized.

The impacts of plastic varies according to the type and size of the debris and can occur at different levels of biological organization in a wide range of habitats [1]. Encounters between plastic litter and organisms can negatively affect individuals, and there is evidence that a substantial proportion of some populations encounter plastic litter; for example, over 40% of sperm whales beached on North Sea coasts had marine litter including, ropes, foils, and packaging material in their gastrointestinal tract [93], while over 95% of the population of northern fulmar (*Fulmar glacialis*) may contain plastic litter in some European waters [94].

Meso-macroplastic ingestion has been reported in several groups of marine organisms, including seabirds, fish, turtles, and mammals [4, 90, 95–97]. On a few occasions it can be confidently inferred that ingestion of plastic has caused death or injury; for example, one juvenile turtle had been found to ingest enough plastic to occupy a major part of the stomach and this was very likely the cause of death [98]. A recent study on Franciscana dolphins accidentally captured by fisheries in Argentina found that 28% of the animals had plastic debris in their stomachs [99]. Packaging debris (cellophane, bags, and bands) were found in just under two-thirds of these dolphins, while just over a third had ingested fragments of fishing gear (monofilament lines, ropes, and nets). Ingestion of plastic has been reported to be high in recently weaned dolphins, this could be a consequence because young dolphins are still learning how to catch prey and could misidentify plastic as food [99].

The impacts of macroplastics on biota are more fully understood than impacts of

microplastics. However, the potential for ingestion is greater with pieces in the microplastic size range since their small size makes them readily accessible for ingestion by a wide range of organisms [100] including whales, fishes, mussels, oysters, shrimps, copepods, and lugworms [101–104]. The impacts of microplastics are discussed in Chapter 21.

Marine organisms may also become entangled in plastic debris (Fig. 22.3); particularly macroplastic. Kühn et al. [96] reported that around 340 species are known to have become entangled in marine debris; this includes over 161 species of marine mammals, sea birds, and turtles. Images of a turtle or seal entangled in fishing gear, or the stomach of a young dead albatross full of plastic objects, are arresting and can be distressing for the observer as well as the animal.

In waters around the United Kingdom, surveys indicate the incidence of entanglement ranges between 2% and 9% for some populations of seabirds and marine mammals [1]. Abandoned, lost, or discarded fishing gear is

one of the main categories of debris resulting in entanglement and accounts for many reports of harm or death on a global scale [105]. Evidence of harm from entanglement is easier to observe, and hence report, than ingestion. This is because ingestion typically only becomes apparent when the carcass of an animal is open—either as a result of dissection or decomposition.

Marine plastics can have further significant ecological impacts. Plastic objects undergo biofouling because they can host a wide size range of organisms [106]. This is of concern as plastic waste can be a mode of transport for species, potentially introducing species into an environment where they were previously absent [106].

Plastic debris can also act like a blanket smothering the seabed. This can prevent gas exchange which can lead to anoxia or hypoxia (low oxygen levels). It can also create artificial hard grounds which could cause problems especially for burying creatures [37, 95, 107]. This could encourage the invasion of species that prefer hard surfaces and, as a result, indigenous species may be



FIG. 22.3 Fur seal tangled in plastic debris (British Antarctic Survey).

displaced; particularly those normally occupying sandy and muddy bottom types. Katsanevakis et al. [108] investigated the effect of marine litter on benthic (seafloor dwelling) animals by purposefully placing litter on the seafloor of Greek coves [108]. In areas with litter, there was an increase in the number of species and individuals, either because the waste provided refuge or because species which are typically found on hard surfaces, such as barnacles and sponges had the opportunity to settle.

5.2 Impacts on Maritime Industries, Tourism, and Human Health

The presence of litter in the marine environment presents an esthetic issue with economic repercussions for the tourist industry, a hazard

for numerous marine industries (e.g., shipping, fishing, energy production, aquaculture) and entanglement/damage of maritime equipment (e.g., propellers on vessels) [4, 11]. It is also considered that litter within the marine environment is unsightly and detracts from the inherent value of the world's coastlines, which can further impact human well-being and socioeconomic activities (Fig. 22.4) [10]. As discussed, plastic is the main constituent of marine anthropogenic litter due to its high persistence within the marine environment [11, 23, 35, 65, 110].

It has been reported that beach choice is more strongly determined by clean, litter-free sand and seawater than by safety [111]. For example, 85% of 1000 residents and tourists said they would not visit a beach with an excess of two litter items per meter [112, 113]. A study in Cape

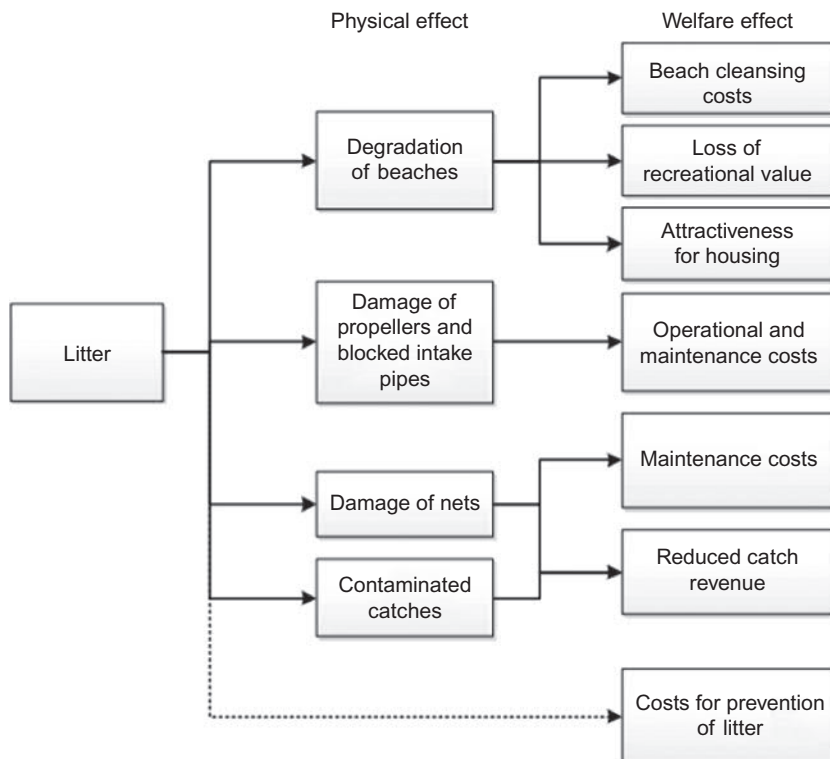


FIG. 22.4 Impacts of beach and marine litter on socioeconomic activities [109].

Town estimated that a loss in the standards of cleanliness on the beaches would result in a 97% loss in the value of those beaches [112]. It was also found that in Geoje Island, Korea, marine debris cost the island US \$29–37 × 10⁶ in tourism losses following an extreme rainfall event in 2011 [114].

There is also emerging evidence that even small quantities of litter on beaches can have a negative effect on human well-being [115]. Wyles et al. [116] found that the restorative psychological benefits ordinarily experienced by people visiting the coast were undermined by the presence of relatively small quantities of litter.

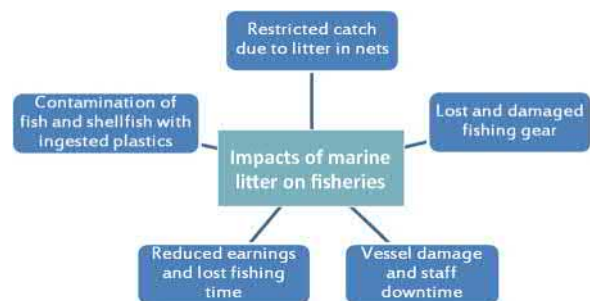
Cleanup programs for anthropogenic litter can be ineffective and expensive. The total cost of removing litter of all types from 34 United Kingdom harbors was estimated at approximately £236,000. Based on this, it was estimated that marine litter costs the ports and harbor industry in the United Kingdom approximately £2.1 × 10⁶ each year [117]. Very limited research has therefore been conducted into the costs of marine litter removal and estimates tend to be based mostly on anecdotal evidence. Research in 2000 found that 56 United Kingdom local authorities spent a total of £2,197,138 a year on beach cleansing, taking into account the cost of collection, transport, disposal charges, work-force, equipment, and administration [118].

Fishing also can be impacted by macroplastic debris (Fig. 22.5). Decreases in the abundance of stocks would directly affect the fisheries economy [10]. However, the most important impact

of macroplastic debris on fisheries is from ghost fishing from Abandoned, Lost or Otherwise Discarded Fishing Gear. Ghost fishing occurs when passive gears such as gillnets, trammel nets, wreck nets, pots, and traps are lost or discarded. These then continue to catch commercially important species of fish and crustaceans as well as noncommercial species of fish and crustaceans, birds, marine mammals, and turtles [119]. It has been estimated that there is an annual loss of 208 t of Antarctic toothfish (*Dissostichus mawsoni*) due to lost longlines [120]. Another study in Australia found that collapsible trawl mesh pots could unintentionally catch 670,866 Blue swimmer crabs (*Portunus pelagicus*) per year.

Additionally, plastic litter can damage vessels or present navigational hazards. It can lead to injury or death following loss of power, due to entangled propellers or blocked water intakes and collision with floating or semisubmerged objects, including (plastic) insulated shipping containers [121]. For example, in 2005, the United States coastguard reported that collisions with submerged objects caused 269 boating incidents, resulting in 15 deaths and 116 injuries [122]. The seriousness of the potential consequences was highlighted by the sinking of the Ferry M/V Soe-Hae in 1993 which was, in part, caused by rope around the propellers, and resulted in 292 deaths [123]. Clearly, the frequency of these negative impacts will increase in relation to increasing levels of contamination. Furthermore, there is potential of harm due to entanglement when swimming and diving.

FIG. 22.5 Potential impacts of marine litter on fisheries. Based on J. Mouat, R. Lopez Lozano, H. Bateson, *Economic Impacts of Marine Litter*, Kommunes Internasjonale Miljøorganisasjon (KIMO International), Lerwick, 2010.



6 SOLUTIONS

The potential threats to aquatic ecosystems presented by plastic debris have been identified as a major global conservation issue and a key priority for research [54]. Critically, it must be recognized that the accumulation of plastic in the oceans is actually a symptom of a wider more systemic problem of linear use of materials and the rapid accumulation of waste, including end-of-life plastic. Even in the absence of complete information on distribution and impacts, it is clear that the key action must be to reduce the quantity of litter entering the oceans from the land.

Current rates of entry for litter into the marine environment far exceed the potential for removal by cleanup, which is very difficult to implement. Therefore the key priority must be to reduce the quantity of litter entering the sea. Prevention can work at the level of production of plastic in terms of redesigning products to use less plastic, design for reuse/recycling, and reduced packaging material. For these interventions to be successful, there may need to be a value placed on disposable products to encourage their reuse and encourage manufacturers to design for recyclability.

In terms of targeting specific products, labels could be instrumental in informing consumers of the plastic content of the product, its ease of recycling, or indeed its potential consequences in the environment. Prevention can also work at the level of plastic becoming waste with the use of targets, taxes, and bans, but these must be carefully implemented to minimize the risk of unintended consequences. However, such measures must go alongside education so that consumers fully understand the implications of the labels and impacts of plastic waste.

Education and outreach programs to modify behavior could be very successful for reducing the amount of litter entering our oceans. For example, a study by Hartley et al. [124] found

that school children in the United Kingdom significantly improved their understanding of the causes and negative impacts of marine litter after education intervention related to plastic marine debris. Education and behavioral change of children is crucial as they have an important influence on their peers, parents, and community [124].

Taxes introduced on plastic items can also be instrumental in changing consumer behavior toward plastic. A fifteen euro cent tax on plastic bags in Ireland led to a 90% reduction of plastic bag usage in the early 2000s [125]. The tax has successfully removed the widespread use of plastic bags throughout Ireland and has started similar taxes globally. In San Francisco, a ban on standard plastic bags has been introduced forcing the use of alternative bags or biodegradable materials [126]. Unfortunately, these taxes do not always work efficiently. South Africa has struggled to achieve similar reduction rates in plastic bag usage through taxes [127]. Taxes alone may not solve the problem of urban plastic, but they are instrumental in reducing usage [10].

Although prevention is a priority, due to the amount of plastic waste already in the environment, cleanup initiatives are still very worthwhile. These can be combined with monitoring exercises and also the involvement of local communities. Benefits of citizen-focused activities such as beach cleaning are also well recognized for their educational value as well as in terms of the litter removed [12]. Annual cleanup operations are now organized in many countries [11] and are often run by voluntary organizations. They can remove substantial quantities of litter from beaches and the coastline. Volunteer involvement in two of the largest cleanup schemes in the United Kingdom (Marine Conservation Society Beach Watch and Keep Scotland Beautiful National Spring Clean) has been estimated to provide a value of approximately £119,500 in terms of cleaning, which suggests that the total cost of voluntary action to remove marine litter is considerable [117].

While awareness is being raised by opportunities associated with relatively low-cost volunteer-led beach cleaning activities, there are concerns about the viability and efficiency of large-scale mechanical cleanup operations at sea. If cleanup operations are seen as a substantive solution, it must be acknowledged that there will be a need for such cleanup in perpetuity. Therefore the main priority must be to focus on preventing litter entering the oceans in the first place and a better understanding in the behaviors that lead to littering, as well as those that lead to engagement in recycling [128]. Most plastics are inherently recyclable, yet many single-use items are not designed so as to be compatible with recycling. A key challenge therefore is to ensure end-of-life disposal via recycling is appropriately considered at the design stage.

Globally, better waste management is a focal point in reducing plastic in the environment. Incorrectly managed landfills may cause waste to reach the environment. Regular long-term monitoring of marine litter is necessary to establish the efficacy of any interventions and to fulfill the requirements of policy such as the European Union's Marine Strategy Framework Directive [129]. Monitoring may also help identify trends, sources, and pathways [130]. There are also circumstances in which waste management will not suffice in stopping plastic leaking into the ocean. For example, in the immediate aftermath of a tropical storm, resource management is focused on human health, toxic spills, and air quality as opposed to waste management [131].

7 SUMMARY

Macroplastic presents an esthetic issue, with economic repercussions for the tourist industry and hazards for numerous marine industries, including shipping and fishing. Plastic debris can also result in physical harm and mortality to marine organisms and there is emerging

evidence of effects at higher levels of biological organization. Once in the ocean, plastic debris has the potential to travel considerable distances from its original location. One of the major challenges in addressing the issues surrounding marine plastic debris is the diverse nature of plastic products and the many routes by which they can enter the environment. To help manage and reduce emissions it is essential to better understand the relative importance of these sources and to assess regional variation. Strategies and policies should also be in place to minimize the amount of plastic waste produced and promote appropriate waste management, for example, via recycling. For effective long-term change, it will be particularly important to apply these solutions internationally so as to minimize inputs of plastic litter into the ocean at a global scale.

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Further Reading

Plastic Waste: How Plastics Have Become Part of the Earth’s Geological Cycle

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1 INTRODUCTION

Human industry produces a wide variety of waste material in solid, liquid, and gas form, which can have many deleterious consequences, from the local to the global scale. Among these, plastics have in recent years become one of the substances of greatest concern, as awareness has grown of the scale and extent of waste plastics, and of their harmful effect upon the biosphere. Although plastics are not produced in such large amounts as are other human-produced solid materials such as, say, concrete [1], their properties mean that they can be spread much more swiftly and widely by wind and water.

Plastics—industrially produced long-chain polymers mostly made from hydrocarbon feedstocks—are light, strong, easily moldable, and resistant to decay. They have become ubiquitous in and seemingly indispensable to modern life, being used in myriad ways as structural elements in infrastructure and tools, as food and goods wrapping, in fibrous form in clothes, nappies and wet wipes, and so on [2]. Initially in the early 20th century, plastic forms, such as bakelite and shellac, were few and their uses restricted, but their use as regards both volume and diversity exploded from the mid-20th century onward, as forms such as nylon, polyethylene (PE), polystyrene (PS),

polyvinyl chloride (PVC), and polyurethane (PUR) were synthesized. These were joined a little later by polypropylene (PP) and then, from the 1970s, polyethylene terephthalates (PET) from which most drinks bottles are now made. There are now ~ 20 main plastics types, with development continuing apace for a multitude of applications (Figs. 23.1 and 23.2).

Manufactured amounts grew from $\sim 2 \times 10^6$ t (2 million metric tonnes) in 1950 to about 380×10^6 t annually in 2015 [5, 7] (Fig. 23.2)—a mass roughly equivalent to the weight of the global human population—and continues to grow, with a projected sixfold increase to about 1800×10^6 t annually by the mid-21st century. The total amount produced on Earth was assessed [7] as 8.3×10^9 t (8.3 billion tonnes) by 2015 (given current rates of growth, by 2018 it will now be some 9.5×10^9 —enough to wrap

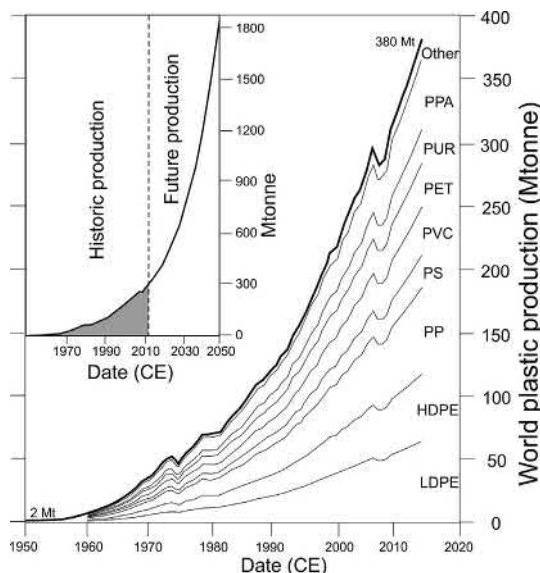


FIG. 23.2 Growth of plastics production from 1950 to 2016 (data from [4, 5, 7]) and projection for future production to 2050 [6].

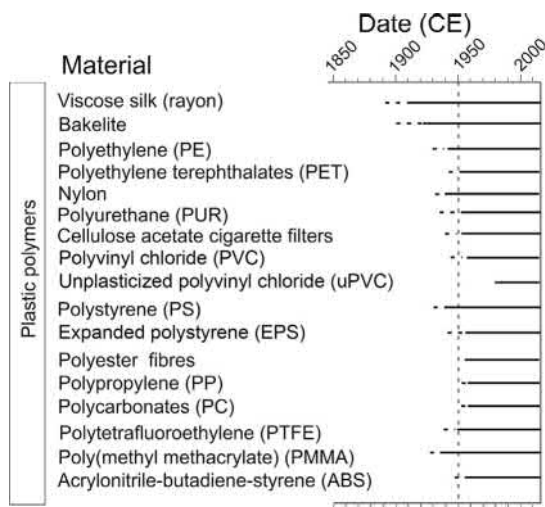


FIG. 23.1 History of appearance of some major types of plastics and plastic artifacts. Based on J. Zalasiewicz, C.N. Waters, J. Ivar do Sul, P.L. Corcoran, A.D. Barnosky, A. Cearreta, M. Edgeworth, A. Galuszka, C. Jeandel, R. Leinfelder, J.R. McNeill, W. Steffen, C. Summerhayes, M. Waprich, M. Williams, A.P. Wolfe, Y. Yonan, *The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene*, *Anthropocene*, 13 (2016) 4–17, <https://doi.org/10.1016/j.ancene.2016.01.002> (web archive link) and information mostly in Ref. [3].

the entire Earth in about two layers of clingfilm (plastic wrap). It is the fate of much of that plastic, postmanufacture, as waste, that has raised increasingly acute environmental concerns [8, 9] that we discuss later. We focus on plastics as a new, and growing, component of the Earth's geology, traveling as sedimentary particles along long and often complex pathways through the Earth's surface sedimentary systems. This approach provides a planetary context to this emergent and troubling phenomenon and may help develop answers to the many questions that plastics pose.

2 PLASTICS AS AN ENVIRONMENTAL PROBLEM

Of the 8.3×10^9 t of plastic produced by 2015 [7], some 2×10^9 t were in use, 0.6×10^9 t were recycled, and 0.8×10^9 t were incinerated. The remainder, 4.9×10^9 t, had been discarded, within landfills, open dumps, and more generally

dispersed as litter. It is this enormous, and growing, disposed mass that is the source of the environmental plastic pollution that has spread widely across our planet, both on land and in the oceans. Although plastics have been generally regarded as inert, their capacity to inflict biological harm, especially as microplastics, in a range of ways is considerable [10, 11]. These figures dwarf the as yet tiny fraction that has so far leaked into the oceans, at between 4.8×10^6 t and 12.7×10^6 t by 2010 [12] and which has triggered much concern because of its already considerable impact on biota. This plastics leakage was projected to increase by an order of magnitude by 2025 [12] and we examine here some of the factors, beyond the simple rise in plastics manufacture, linked to this predicted increase.

Reports of plastics as environmentally harmful, first surfaced from the 1960s—that is, with a lag of 1–2 decades following the beginning of societal use—with reports of seabird populations being affected [13] and of plastic floating in the sea [14]. Few studies have cored terrestrial and marine sediments to investigate whether the timing of plastic contamination broadly coincides with the scale of plastic production rates, though a study of sites onshore in Japan and offshore in Thailand, Malaysia, and South Africa [15] confirmed that microplastic pollution started in the 1950s and increased continuously upward through younger sediments. Realization of the enormous scale of plastics pollution is essentially a feature of this millennium, exemplified by the discovery of the “Great Pacific Garbage Patch,” trapped as flotsam in the North Pacific gyre [16], estimated to include at least 79,000 t of floating plastic [17]. In the last decade, a number of studies have established the extent of plastics pollution in the marine realm, with studies of coastlines [18, 19], continental shelves and the open ocean at both the sea surface [17, 20, 21], and the deep sea floor [22, 23]. A good deal of recent attention has focused on microplastic particles (those less than 5 mm in diameter), which include fibers, detached from

plastics-based textiles, and microbeads [20, 24–27].

3 FACTORS AFFECTING THE TRANSPORT OF WASTE PLASTICS THROUGH THE ENVIRONMENT

When natural sedimentary particles travel across the surface environment, a number of factors are seen to affect the way they travel, most notably their density, size, and shape, which determine how they respond to currents of wind and water (and which also affect how they interact with biological organisms, including humans). Most plastics are low-density materials by comparison with most rocks and minerals, and so in general they are more easily transportable than these by both wind and water. Thus they travel relatively rapidly, and far, across the Earth, as observation has shown [18, 21]. A key threshold is whether they are more dense than water, and so sink (e.g., PVC film with a density of 1.3 g cm^{-3} and PET bottles of 1.39 g cm^{-3}), or whether they are less dense, and float (e.g., PE plastic bags of 0.95 g cm^{-3} and PP of 0.92 g cm^{-3}) [28]. Most plastics have densities not far off that of water, so if they sink, they sink slowly, and if they float, a slight increase in density (for instance, as marine organisms, or sediment grains, become attached to them) will mean that they will begin to slowly sink. In any of these cases, they are prone to being transported long distances, even by gentle currents of water, before finally settling to the floor of a lake, river, or sea, where they are now widely observed ([29]; and see later).

Environmental plastics—those leaked deliberately or accidentally into our environment—are commonly classified by size into macroplastics (>5 mm), microplastics (<5 mm), and nanoplastics (a few tens of nanometers or less). Macroplastics include all the easily visible trash, such as plastic bags and bottles, and discarded cigarette filters, wet wipes, plastic toys,

and fishing nets; this is the component recovered and measured in such efforts as beach cleaning programs. Microplastics include primary particles which were originally manufactured in that form, such as the plastic microbeads made for cosmetic use, and also the lentil-sized “nurdles,” transported in bulk as a precursor to plastics goods manufacture. Microplastics also include substantial quantities of secondary fragments shed from macroplastic objects, a key component being fibers derived from the plastics-based textiles that make up most contemporary clothing. Such microplastics occur in extraordinary amounts: a single domestic laundry cycle can shed something like 140,000 fibers from polyester-cotton blend fabric, nearly 500,000 fibers from polyester and nearly 730,000 from acrylic [30] and these particles are too small to be trapped by the filters installed in municipal sewage plants. A wastewater treatment plant for a population equivalent of 650,000 people can discharge 65 million microplastics per day, despite a ~98% reduction compared with the influent [31]. Hence, fibers can pass straight through into the rivers, and through these into the sea, where they are now virtually omnipresent (see later). Such observations open the possibility of recognizing seasonal variations in synthetic fiber abundance in laminated sediments, with greater abundance of microfibers potentially associated with the enhanced usage of washing machines and more clothing worn in winter times [20]. Nanoplastics are likely to be similarly widespread, but they remain relatively little studied, partly because of a lack of suitable methods to detect nanoplastics in samples [32].

Atmospheric microplastics (usually as fibers) are now recorded from several sites, and in the city of Paris, for example, fallout concentrations of up to 355 particles per square meter per day have been recorded: this equates roughly to between 3 and 10t of fibers deposited by atmospheric fallout every year for the Paris agglomeration [33].

Plastic shape strongly influences how plastics travel through the environment, the extraordinarily wide variety of manufactured form rendering this an exceedingly complex phenomenon to study: one might consider the aerodynamic and hydrodynamic differences between spheres (microbeads, nurdles), tubes (solid or hollow, or closed at one end, as in bottles), sheet-like forms, bags, nets, and so on. Interactions with mineral sediment will add additional complexity: discarded plastic bottles may or may not become sediment filled; a simple PE sheet might accumulate an algal fouled layer, increasing its density slightly, while in a discarded piece of textile the fibers can become sediment-clogged, with a significantly greater increase in relative density. Microplastic particles may be sufficiently abundant in the sediment to affect properties such as sediment porosity and permeability and may also affect the deposit-feeding animals which churn through sediment to feed. Such factors, interacting with the topography of land surface and sea floor and with vegetation trapping plastics, will help determine where plastic pollution will tend to pile up and where it will be more thinly dispersed. Study of these factors is in its infancy.

4 PLASTICS DECAY

In general, plastics are a novelty to the Earth System, and this is one reason for physical and chemical durability—few organisms (see later) have evolved the ability to break down their chemical structure; this makes plastics persistent in the environment, perhaps over geological timescales.

A key reason for the success of plastics lies in their resistance to biological and chemical attack. This is not quite absolute. Cellulose-based materials such as “cellophane” are comparable in biodegradability to paper, but their market share has shrunk sharply in recent decades as they are more expensive to make

and less versatile than are petroleum-based plastics. Among the petroleum-based plastics, the most widely reported kind of breakdown is the effect of the UV component of sunlight, which slowly breaks the chemical bonds and makes it become brittle; this will eventually cause plastic to degrade to microplastic fragments, but apparently not completely into individual monomers [34, 35].

Studies have shown that the Antarctic krill (*Euphausia superba*) fragment plastics, once ingested, into pieces less than 1 μm in diameter [36]. Biological digestion of plastics has also been reported. Some species of microbes can digest some plastics [37], and there has been a report that a wax moth in its caterpillar stage (the normal habitat of which is in beehives, where they feed on beeswax) can eat and digest PE film [38]. The effect of such biodegradation currently seems negligible in practice, though whether it may be enhanced in future (the current abundance of near-surface plastics suggests that there would be a selective advantage in evolving the biochemical means to digest it) is uncertain.

Both UV-caused degradation and any biological processing are more likely to take place in surface or near-surface conditions. It is less clear what happens to plastics that are buried in sediment layers or in landfills. These will be in darkness (so no UV effects) though in a wide variety of chemical and biochemical microenvironments, depending on what other waste materials they are buried with. The long-term persistence of plastics in such conditions has been little studied, but empirical observation of such sedimentary or landfill layers when they are reexposed by digging or erosion [39] suggests little obvious alteration of the plastics over at least a few decades.

The nearest natural analogs to plastics suggest that some might persist over geological timescales. Natural long-chain polymers such as those that form the outer casings of pollen and spores, amber, and the housings of

graptolites (extinct Paleozoic macrozooplankton inhabiting “tubaria” of a collagen-like substance) may be preserved for many millions of years, and some can survive long-distance marine transport even following subsequent exhumation, to become components of a new generation of strata.

It is evident, therefore, that waste plastics already in the environment may persist over a number of human generations and, depending on circumstances, potentially far longer. In this longevity they may rival artificial radionuclides, where management plans need to project into the future over many thousands of years. Tracking the long-term pathways of plastics, hence, is important to any attempt at management.

5 PLASTICS IN THE TERRESTRIAL ENVIRONMENT

The distribution of plastic waste on land and in freshwater systems is counterintuitively, rather less well understood in a number of respects than is plastic waste in the ocean [40, 41]. This is because of its great variability in distribution, with very considerable regional and local differences, which depend upon such factors as social culture, national wealth, legislative frameworks, and technical means of disposal.

Even within Europe, a region with relatively sophisticated and harmonized environmental regulation and data collection, there are wide variations and considerable uncertainties. In 2016 Europe produced some 60×10^6 t of plastics [5], about one-sixth of global production. In the same year, less than half this amount, 27.1×10^6 t, was registered as “collected waste” [5], suggesting that the “uncollected waste” category of more casually disposed plastic litter is of considerable scale. Within the recorded plastic waste there was a moderately consistent level of recycling, at 20%–40% (though much of this is “downcycling” to a lower grade product), while the amount going to landfill varied from <5%

(e.g., Scandinavia, Switzerland, Germany, where most waste plastics are incinerated) to >70% (e.g., Bulgaria, Croatia, Greece) [5]. The stores of plastic accumulating on land, therefore, show strong regional differences.

These differences are amplified on the world scale. In the United States, proportionately fewer plastics are recycled and more ($\sim 75\%$ or $\sim 25 \times 10^6$ t in 2014) go into landfill [42]. In rapidly industrializing developing countries, particularly those with less mature regulatory regimes, a higher proportion of plastics is discarded as litter, or stored in open landfills, from which they can be easily remobilized into the surface sedimentary cycle.

On land, plastic is sequestered within the fabric of infrastructure, such as buildings, disposed of within landfill sites and disseminated as litter, with plastic in use destined for landfill or casual disposal with a time frame varying from days to decades. From land stores, plastics are increasingly leaking into the sea, by a variety of pathways, but with river transport predominant, particularly along rivers flowing past the world's large urban conurbations [12]. Plastics are pervasive in these rivers, albeit with strong variations in space and time; following flood events, the amount of microplastics in river sediments has been shown to decrease sharply, indicating that they have been effectively flushed seawards [43]. Also, the banks of rivers and estuaries can be a significant sink of microplastics, with a study in the Clyde Estuary showing abundant synthetic fibers downstream of the outlet from a sewage treatment plant, with the size and number of fibers decreasing the greater the distance downstream of the outlet [44].

6 MARINE PLASTICS

Although the ocean, and particularly the deep sea floor, is generally regarded as less easily accessible than is the land surface, an overall picture is emerging of the wide (becoming near-ubiquitous) extent of marine plastics. This

reflects both the ease with which plastics are transported by wind and water from land to the sea, and the commonly very long transport paths in the ocean, which leads to extensive distribution. Most studies have been of floating plastics at the sea surface, and of plastics on the sea floor, either by direct observation of macroplastic fragments [17, 29, 45] or by sampling of seawater/sea floor sediments for microplastics [18, 21, 23].

Plastic is most easily observed at coastlines, where it is concentrated by the beaching of plastic flotsam, which has often traveled long distances across the ocean. For example, on Henderson Island in the remote Pitcairn Islands has the highest density of plastic debris ~ 670 items per square meter reported anywhere in the world [19]. Records of abundant plastic, both macroplastics [34] and microplastics [20, 26] suggest that plastics are now virtually ubiquitous on beaches worldwide, and both scientific and beach cleaning programs are providing considerable data on its extent. Similarly, lakeshores are also susceptible to plastic accumulations with concentrations similar to those in ocean gyres reported [46].

Plastics floating in the open ocean have been estimated to weigh 250,000 t at any one time, and to comprise some 5 trillion (5×10^{12}) pieces, mostly macroplastics [47]; there are lower estimates of open-ocean surface plastics of between 7 t and 35,000 t [45], with alternative estimates of 15 to 51 trillion microplastic particles, weighing between 93,000 t and 236,000 t [21]. There are concentrations in the mid-ocean gyres such as the "Great Pacific Garbage Patch" [16, 17, 21], where plastics can be present in greater quantity than zooplankton.

Plastics are also ubiquitous on the deep sea floor, where macroplastic distribution is being increasingly charted and placed on databases, for example, of deep sea submersible and ROV images [29]. This showed macroplastics being recorded in most dives and present even in the deepest oceans (e.g., at >10 km depth in the Marianas Trench). Sampling ocean floor

sediments for microplastics showed yet greater ubiquity, with a number of studies [18, 23, 48] finding microplastics, mainly as fibers, present in virtually every sample; even those remote parts of the ocean floor with the lowest abundances (seamounts on the Indian Ocean floor) showed concentrations of ~4000 fibers per square meter. These abundances were orders of magnitude greater than in the surface waters above and suggests that even low-density plastic fibers quickly descend to the sea floor; the mechanism is probably via ingestion by plankton and then falling as part of “marine snow,” either within fecal pellets or within the bodies of dead plankton [49, 50].

7 DISCUSSION: THE SEDIMENTARY TRAJECTORY OF PLASTICS

It is now clear that plastic debris is widely distributed across the Earth, in both terrestrial (including fluvial and lacustrine) and marine

environments (Fig. 23.3). It is in the oceans that concern has been most acute, given the obvious, vivid, and widely broadcast examples of harm to marine organisms. A key question is how much worse the situation might get, given that the amounts of plastics both entering the oceans, and afloat within them, are orders of magnitude smaller than the amount of plastics stored on land, and the volumes of plastics currently being manufactured and projected to be produced in coming decades (Fig. 23.2).

Geological considerations—viewing plastics as components of Earth’s sedimentary cycle—point to some key questions. First, what factors will affect plastics delivery to the oceans? Clearly some of these factors are societal, relating to the future management of both production and of waste by means such as legislation, education, and research. However, there are too the current $\sim 5 \times 10^9$ t of legacy plastic waste [7] both dispersed across the land surface and disposed of within landfills. Much of the former will eventually find its way to the sea, as will some part of the latter. For even a well-designed

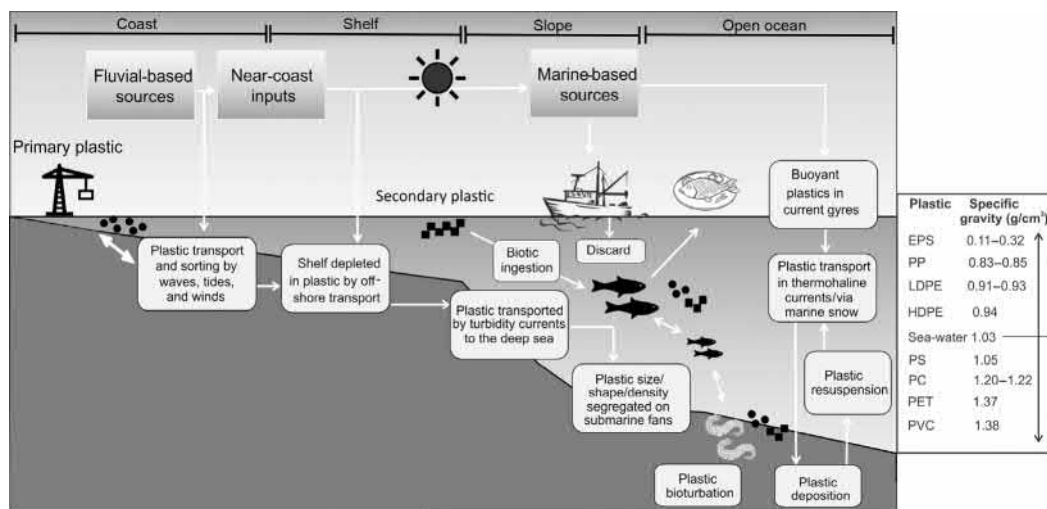


FIG. 23.3 Plastics pathways in the oceans. Modified from J. Zalasiewicz, C.N. Waters, J. Ivar do Sul, P.L. Corcoran, A.D. Barnosky, A. Cearreta, M. Edgeworth, A. Gatuszka, C. Jeandel, R. Leinfelder, J.R. McNeill, W. Steffen, C. Summerhayes, M. Waprich, M. Williams, A.P. Wolfe, Y. Yonan, *The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene*, *Anthropocene* 13 (2016) 4–17, doi:<https://doi.org/10.1016/j.ancene.2016.01.002> (web archive link).

landfill, on long geological timescales, there are only two options: tectonic subsidence to become buried beneath newer strata and taken to lower crustal levels; and erosion on stable or rising crust, with the contents being washed into the sea. This scenario is further modified by coastal effects, active on shorter timescales, as waves erode coastal landfills, releasing their contents directly to the coastal zone. This kind of erosion, remobilizing buried plastics, is already taking place, even with normal coastal retreat and a global sea level that has so far only risen ~20cm over the past century [51, 52]. As sea level rises over future decades, the transgression of the erosive coastal zone farther inland will cause migration of this erosive zone, affecting landfills currently out of reach of wave action.

Another factor affecting the future supply of legacy plastics into the oceans is the physical and chemical state of plastics after decades (and ultimately centuries, then millennia) of burial in a variety of physical-chemical microenvironments that might be expected given the extreme heterogeneity of landfill deposits [53]. This factor is largely unconstrained and is a key unknown (and indeed comprises a range of unknowns, reflecting the range of different plastic types in production).

Once released into the ocean, a further factor is the rate at which plastics become incorporated into accumulating strata, as this will determine the rate at which they are effectively taken away from the zone of harmful interaction with biological organisms, to become permanently sequestered (and ultimately fossilized). Such burial to be effective needs to be deep enough not to interact with the sediment-dwelling burrowing biota—that is, below the redox interface—and permanent (for many surface sediment accumulations are prone to erosion and remobilization of their constituent particles) [54].

Currently, much focus on environmental plastic is on their surface pathways and distribution and the nature of their complex interactions

with a range of organisms (including humans). The longer term, and largely subterranean, aspects of the geological behavior of plastics are by contrast as yet little studied, though they will to a considerable degree determine the long-term evolution of plastics in the oceans. Plastics have already become a characteristic feature of the Anthropocene, the epoch proposed [55, 56] to signify growing human domination of Earth surface processes. Even a cursory examination of the factors at work here suggests that they will remain a significant part of the marine realm for a long time into the future.

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Air Pollution: Atmospheric Wastes

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1 INTRODUCTION

Air pollution is the presence of contaminants or substances in the air that interfere with human health or welfare, or produce other harmful environmental effects [1]. This definition requires context, that is, something is an air pollutant if it causes conditions to deviate from a desired state. Thus an air pollutant interferes a benchmark of a desired condition that, at a minimum, provides for air quality that supports human and other life. However, the

definition goes beyond health and extends to welfare, including ecological condition and societal well-being. From a systems perspective, all of these desired states are, in fact, a single desired state. Pope Francis put this succinctly in his encyclical letter, *Laudato Si'*:

Some forms of pollution are part of people's daily experience. Exposure to atmospheric pollutants produces a broad spectrum of health hazards, especially for the poor, and causes millions of premature deaths. People take sick, for example, from breathing high levels of smoke from fuels used in cooking or heating.

There is also pollution that affects everyone, caused by transport, industrial fumes, substances which contribute to the acidification of soil and water, fertilizers, insecticides, fungicides, herbicides and agrotoxins in general.

From a strictly thermodynamic standpoint, the pollutant is the result of inefficiency. An air pollutant is mass or energy that is exiting a control volume. In trying to produce something of value, a waste is released to the atmosphere. In environmental connotations, the term “waste” generally applies to either materials that find their way to the land and soil. Materials found in water and air are referred to as pollution. This is a distinction of convenience and regulation, not one of science. Thus this chapter focuses on the waste streams that affect the atmosphere.

2 AIR POLLUTION

For centuries, people have known intuitively that something was amiss when their air was filled with smoke or when they smelled an unpleasant odor. But, for most pollutants, those that were not readily sensed without the aid of sensitive equipment, a baseline had to be set to begin to act. One way to look at the interferences mentioned in the definition is to place them within the context of “harm.” Harm can be acceptable, so long as it is sufficiently unavoidable and arises only as a result of some more favored good. The objects of the harm have received varying levels of interests. In the 1960s, the perception of harm to ecosystems grew as larger number of people perceived that the very survival of certain biological species was threatened and that these threats extended to humans. Indeed, the direct harm to humans was perceived earlier than those to ecosystems, especially in terms of diseases directly associated with obvious episodes, such as respiratory diseases and even death associated with combinations of weather and pollutant releases [2].

Myriad atmospheric wastes have accompanied the industrial and technological eras. Nuclear power plants are associated with the possibilities of meltdown and the release of airborne radioactive materials. Burning of fossil fuels releases products of incomplete combustion, for example, polycyclic aromatic hydrocarbons. Even complete combustion releases the greenhouse gas, carbon dioxide (CO_2). Leaks from chemical, pesticide, and other manufacturing facilities may cause exposures to toxic substances, such as the release of methyl isocyanate in Bhopal, India. In the last quarter of 20th century, these apprehensions led to the public’s growing wariness about “toxic” chemicals added to the more familiar “conventional” pollutants like soot, carbon monoxide, and oxides of nitrogen and sulfur. Toxic chemical exposures were increasingly linked to cancer and threats to hormonal systems in humans and wildlife, neurotoxicity (notably from lead and mercury exposure in children), and immune system disorders.

Some substances thought to be almost exclusively water or food contaminants were found in the air. For example, the source blood lead (blood-Pb) levels in children were initially thought to be pica, that is, eating chips of lead paint. However, the Pb concentrations declined precipitously in children living near roadways following the decreased use of tetraethyl-lead and other Pb organometallic compounds in gasoline, which may have accounted for more than half of blood-Pb in the 1970s [3].

Growing numbers of studies have provided evidence linking disease and adverse effects to extremely low levels of certain particularly toxic substances. For example, exposure to dioxin at almost any level above what science could detect could be associated with numerous adverse effects in humans.

At the threshold of the new millennium, new atmospheric waste problems were identified, including the loss of aquatic diversity in lakes due to deposition of acidic precipitation,

so-called acid rain. Acid deposition was also being associated with the corrosion of materials, including some of the most important human-made structures, such as the pyramids in Egypt and monuments throughout the world. Presently, global pollutants have become the source of public concern, such as those that seemed to be destroying the stratospheric ozone layer or those that appeared to be affecting the global climate. This escalation of awareness of the multitude of pollutants complicated matters.

A principal challenge in addressing air pollution, as other wastes discussed in this book, is that most pollutants under other circumstances would be “resources,” such as compounds of nitrogen. In the air, these compounds can cause respiratory problems directly or, in combination with hydrocarbons and sunlight indirectly can form ozone and smog. But, in the soil, nitrogen compounds are essential nutrients. So, it is not always simply a matter of “removing” pollutants, but one of managing systems to ensure that optimal conditions for health and environmental quality exist. Impurities are common, but in excessive quantities and in the wrong places they become harmful.

In the transportation sector, the term “zero emission” has been applied to vehicles, as the logical next step following low emission vehicles (LEVs) and ultralow emission vehicles (ULEVs). However, zero emissions of pollutants will not be likely for the foreseeable future, especially if one considers that even electric cars are not emission free, but are a type of emission trading from a mobile source to a stationary source. That is, the electricity is generated at a power plant that is emitting pollutants as it burns fossil fuels or has the problem of radioactive wastes if it is a nuclear power plant. Even hydrogen, solar, and wind systems are not completely pollution free since manufacture, transport, and installation of the parts and assemblages require energy and materials, some of which finds their way to the atmosphere (see the discussion of life cycles in [Chapter 2](#)).

2.1 Atmospheric Contamination

The predominant concern with atmospheric waste is chemical contamination, which presents a hazard to human health. Thus public health is usually the principal driver for assessing and controlling air contaminants. However, air pollution abatement laws and programs have also recognized that effects beyond health are also important, especially *welfare* protection. One of the main welfare considerations is that ecosystems are important *receptors* of contamination. Another welfare concern is that contaminants impact structures and other engineered systems by corrosion. Thus from an air pollution perspective, there is a cascade of hazards from human health to ecosystems to abiotic (i.e., non-living) systems.

Certainly, not all pollutants are chemical hazards. They can also be physical, such as the energy from ultraviolet (UV) light. Often, even though our exposure is to the physical contamination, this exposure is indirectly brought about by chemical contamination. For example, the release of chemicals into the atmosphere, in turn react with ozone in the stratosphere, decreasing the ozone concentration and increasing the amount of UV radiation at the earth’s surface. This has meant that the mean UV dose in the temperate zones of the world has increased. This has been associated with an increase in the incidence of skin cancer, especially the most virulent form, melanoma.

Air pollutants may also be biological, as when bacteria and viruses are released to the atmosphere from medical facilities. Other biological air pollutants include irritants and allergens, such as pollen and molds (i.e., bioaerosols).

2.2 Legislation

The U.S. Congress enacted the 1970 amendments to the Clean Air Act to provide a comprehensive set of regulations to control air emissions from area, stationary, and mobile

sources. This law authorized the U.S. EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and the environment from the “conventional” (in contrast to “toxic”) pollutants: carbon monoxide, particulate matter (PM), oxides of nitrogen, oxides of sulfur, and photochemical oxidant smog or ozone. The metal lead (Pb) was later added as the sixth NAAQS pollutant. The original goal was to set and to achieve NAAQS in every state by 1975. These new standards were combined with charging the 50 states to develop state implementation plans (SIPs) to address industrial sources in the state.

The ambient atmospheric concentrations are measured at over 4000 monitoring sites across the United States. The ambient levels have continuously decreased, as presented in Table 24.1. The Clean Air Act Amendments of 1977 mandated new dates to achieve attainment of NAAQS (many areas of the country had not met the prescribed dates set in 1970). Other amendments were targeted at types of air pollution that had

not previously been addressed sufficiently, including acidic deposition, tropospheric ozone pollution, depletion of the stratospheric ozone layer, and a new program for air toxics, known as the National Emission Standards for Hazardous Air Pollutants (NESHAPS).

3 SCALE OF THE PROBLEM

Air is polluted at all scales, from cellular to global. A waste manager may be able to rely on air pollution data and reports at the urban or regional scale. These can be subdivided into five ascending scales: local, urban, regional, continental, and global. For situations at finer scales, for example, truck exhaust exposure during refuse collection and recycling, this information may need to be augmented with data on the concentration of certain air pollutants at microenvironmental scale (e.g., indoor air in a home, office, or garage) or personal scale (i.e., at the individual’s breathing zone). The spheres of influence of the air pollutants themselves range from molecular (e.g., gases and nanoparticles) to planetary (e.g., diffusion of greenhouse gases throughout the troposphere). The local scale is up to about 5 km of the earth’s surface. The urban scale extends to the order of 50 km. The regional scale is from 50 to 500 km. Continental scales range from several 1000 km. Of course, the global scale is planet-wide [4].

3.1 Local Scale

Local air pollution problems are usually characterized by one or several large emitters or many relatively small emitters. The local scale is the focus of most waste managers. Indeed, the waste management facility is often a source of air pollution, for example, fugitive dust from a landfill or stack emissions from an incinerator. Thus the waste manager, like any reputable environmental professional, must find ways to ameliorate air emissions.

TABLE 24.1 Percentage Decrease in Ambient Concentrations of National Ambient Air Quality Standard Pollutants From 1990 to 2014

Pollutant and Averaging Time	Decrease in Ambient Concentration
Carbon monoxide (CO) 8-h	77%
Lead (Pb) 3-month average	99%
Nitrogen dioxide (NO ₂) annual	56%
Nitrogen dioxide (NO ₂) 1-h	50%
Ozone (O ₃) 8-h	22%
Particulate matter 10 μm (PM ₁₀) 24-h	39%
Particulate matter 2.5 μm (PM _{2.5}) annual	42%
Particulate matter 2.5 μm (PM _{2.5}) 24-h	44%
Sulfur dioxide (SO ₂) 1-h	85%

Source: U.S. Environmental Protection Agency, *Our Nation’s Air—Status and Trends Through 2016, 2017*. Available from: <https://gispub.epa.gov/air/trendsreport/2017/#highlights>.

Lowering the release height of a source, for example, an incinerator, spreads the potential local impact for a given release. Examples include carbon monoxide and hydrocarbon released from tailpipes or oxides of sulfur released from power plants. In fact, this phenomenon is the reason that certain controls have led to larger scale problems, that is, solving a local air pollution problem by increasing the height of the point of release (i.e., tall stacks) allowed pollutants to travel long distances from the source. Any ground-level source, such as evaporation of volatile organic compounds from a gasoline station, will produce the highest concentrations near the source, with concentrations generally diminishing with distance. This phenomenon is known as a concentration gradient.

Large sources that emit high above the ground through stacks can also cause local problems, especially under unstable meteorological conditions that cause portions of the plume to reach the ground in high concentrations.

There are many releases of pollutants from relatively short stacks or vents on the top of one- or two-story buildings. Under most conditions such releases are caught within the turbulent downwash downwind of the building. This allows high concentrations to be brought to the ground surface. Many different pollutants can be released in this manner, including compounds and mixtures that can cause odors. Usually, the effects of accidental releases are confined to the local scale.

3.2 Urban Scale

Waste managers are part of the decision-making structure of urban areas. They may represent individual towns, cities, or counties in a metropolitan area or be part of a multijurisdictional planning association [5]. Air pollution problems in urban areas generally result from either primary or secondary pollutants. Primary pollutants are released directly from sources, whereas secondary pollutants form through chemical reactions of the primary pollutants in

the atmosphere after release. Air pollution problems can be caused by individual sources on the urban scale as well as the local scale. For gaseous pollutants that are relatively nonreactive, such as carbon monoxide (CO), and relatively slowly reactive, such as sulfur dioxide (SO₂), the contributions from individual sources combine to yield high concentrations. Since motor vehicles are the major source of CO in the ambient air, "hot spots" of high concentration can occur especially near intersections with high traffic. The emissions are especially high from idling vehicles. The hot spots are exacerbated if high buildings surround the intersection, since the volume of air in which the pollution is contained is severely restricted. The combination of these factors results in high concentrations.

Particulate matter (PM) is highly variable in its composition. By mass, the chemical reactivity of the individual particle may range. The liquids and solids that make up the PM often consist of chemically reactive substances, especially those adsorbed onto particle surfaces.

Tropospheric ozone (O₃) is a dominant air pollution problem in many urban areas. It forms from reactions among secondary pollutants in the presence of sunlight's ultraviolet range, that is, photochemical oxidant smog. Many metropolitan areas in the United States are in nonattainment for ozone; that is, they are not meeting the air quality standards. In the United States the Clean Air Act Amendments (CAAA) of 1990 classifies the various metropolitan areas to be in nonattainment according to the severity of the problem for that attainment with the National Ambient Air Quality Standards (NAAQS).

Oxides of nitrogen, principally nitric oxide (NO), but also nitrogen dioxide (NO₂) are emitted from automobiles and from combustion processes. Hydrocarbons are emitted from many different sources. The various species have widely varying reactivities. Determining the emissions of these chemical species from myriad sources as a basis for pollution control programs can be difficult, but methods continue to improve.

3.3 Regional Scale

Three problem types contribute to air pollution problems on the regional scale. The first is the blend of urban oxidant problems at the regional scale. Many major metropolitan areas are merging spatially and continue to grow. Urban geographers refer to some of the larger urban aggregations as “megapolises.” As a result, the air from one metropolitan area, containing both secondary pollutants formed through reactions and primary pollutants, flows on to the adjacent metropolitan area. The pollutants from the second area are then added on top of the “background” from the first.

The second problem involves the release of relatively slow-reacting primary air pollutants that undergo reactions and transformations during lengthy transport times. Protracted transport times, result over regional scales, not only mean long residence times for the parent compounds but of numerous transformation by-products that form during the transport. The gas, sulfur dioxide (SO_2), released primarily through combustion of fossil fuels (especially from coal and oil) is oxidized during long-distance transport to sulfur trioxide (SO_3):



Although SO_2 is a gas, both gas phase and liquid phase oxidation of SO_2 occur in the troposphere. The SO_3 in turn reacts with water vapor to form sulfuric acid:



Sulfuric acid reacts with numerous compounds to form sulfates. These are fine (submicrometer) particulates. Nitric oxide (NO) results from high-temperature combustion, both in stationary sources such as power plants or industrial plants in the production of process heat and in internal combustion engines in vehicles. The NO is oxidized in the atmosphere, usually rather slowly, or more rapidly if there is ozone present, to nitrogen dioxide (NO_2), which also reacts

further with other constituents, forming nitrates, which is also in fine particulate form.

The sulfates and nitrates existing in the atmosphere as fine particulates, generally in the size range $<1\mu\text{m}$ (aerodynamic diameter), can be removed from the atmosphere by several processes. “Rain out” occurs when the particles serve as condensation nuclei that lead to the formation of clouds. If the droplets grow to a sufficient size they fall as raindrops with the particles in suspension or in solution. Another mechanism, known as “washout,” also involves rain, but the particles in the air are captured by raindrops falling through the air. Both mechanisms contribute to “acid rain,” which results in the sulfate and nitrate particles reaching lakes and streams, and increasing their acidity. As such, acid rain is both a regional and continental problem [4].

A third type of regional problem is visibility, which may be reduced by specific plumes or by the regional levels of particulate matter that produce various intensities of haze. The fine sulfate and nitrate particulates just discussed are largely responsible for reduction of visibility. This is especially problematic in locations of natural beauty, where it is desirable to keep scenic vistas as free of obstructions to the view as possible. Regional haze is a type of visibility impairment that is caused by the emissions of air pollutants from numerous sources across a broad region. The CAAA provides special protections for such areas; the most restrictive denoted as mandatory Federal Class I areas that cover over 150 national parks and wilderness areas in the United States [6]. Decreased visibility can also impair safety, especially concerning aviation.

3.4 Continental Scale

In Europe, there is little difference between what would be considered regional scale and continental scale. However, on larger continents there would be a substantial difference. Perhaps of greatest concern on the continental scale is

that the air pollution policies of a nation are likely to create impacts on neighboring nations. Acid rain in Scandinavia has been considered to have had impacts from Great Britain and Western Europe. Japan has considered that part of their air pollution problem, especially in the western part of the country, has sources in China and the Korean peninsula. For decades, Canada and the United States have cooperated in studying and addressing the North American acid rain problem. Likewise, tall stacks in Great Britain and the lowland countries of continental Europe have contributed to acid rain in Scandinavia. British industries for some years simply built increasingly tall stacks as a method of air pollution control, reducing the immediate ground-level concentration, but emitting the same pollutants into the higher atmosphere. The local air quality improved, but at the expense of acid rain at other parts of Europe.

3.5 Planetary Scale

The release of radioactivity from the accident at Chernobyl would be considered primarily a regional or continental problem. However, elevated levels of radioactivity were detected in the Pacific Northwest part of the United States soon after the accident. Likewise, persistent organic pollutants, such as polychlorinated biphenyls (PCBs) have been observed in Arctic mammals, thousands of miles from their sources. These observations demonstrate the effects of long-range transport.

In this and other instances, the gases are released from numerous locations on the earth's surface, but when added together can change the temperature and other climatological features of the troposphere. In the case of chlorofluorocarbons (CFCs), their release results in free chlorine (Cl) atoms that attack ozone (O_3) in the stratosphere, which is ordinarily quite stable and resists vertical air exchange between layers. However, halogen compounds can be transferred from the troposphere into the

stratosphere by injection through the tops of thunderstorms that occasionally penetrate the tropopause, the boundary between the troposphere and the stratosphere. Some transfer of stratospheric air downward also occurs through occasional gaps in the tropopause. Since the ozone layer is considerably above the troposphere, the transfer of chlorofluorocarbons upward to the ozone layer is expected to occur gradually. Thus there is a lag from the first release of these gases until an effect is seen, that is, the so-called thinning of the O_3 layer at the poles. Similarly, with the cessation of use of these materials worldwide, there has been a commensurate lag between in restoration of the O_3 layer.

Other important planetary scale pollutants are the attendant global problem of climate change that is generated by excessive amounts of radiant gases (commonly known as greenhouse gases, GHGs), especially methane (CH_4) and CO_2 , which is not normally considered an air pollutant. A portion of radiation from the earth's surface is intercepted by the carbon dioxide in the air and is reradiated both upward and downward. That which is radiated downward keeps the ground from cooling rapidly. As the carbon dioxide concentration continues to increase, the earth's temperature is expected to increase [7, 8].

4 AIR QUALITY

The main aim in controlling air pollution is to prevent adverse responses to receptor categories exposed to the atmosphere: human, animal, plant, and material. These adverse responses have characteristic response times: short term (i.e., seconds or minutes), intermediate term (i.e., hours or days), and long term (i.e., months or years) (Table 24.2). To elicit no adverse responses, the pollutant concentration in the air must be lower than the concentration level at which these responses occur. Fig. 24.1

TABLE 24.2 Examples of Receptor Category Characteristic Response Times for Exposures to Air Pollutants

Receptor Category	Examples of Receptor Category Characteristic Response Times		
	Characteristic Response Times		
	Short Term (s–min)	Intermediate Term (h–days)	Long term (months–years)
Human	Odor, visibility, nasopharyngeal and eye irritation	Acute respiratory disease	Chronic respiratory disease and lung cancer
Animal, vegetation	Field crop loss and ornamental plant damage	Field crop loss and ornamental plant damage	Fluorosis of livestock, decreased fruit and forest yield
Material	Acid droplet pitting and nylon hose destruction	Rubber cracking, silver tarnishing, and paint blackening	Corrosion, soiling, and materials deterioration

Source: A.C. Stern, R. Boubel, Turner, and DB, Fox, Donald L, in: *Fundamentals of Air Pollution*, 1984.

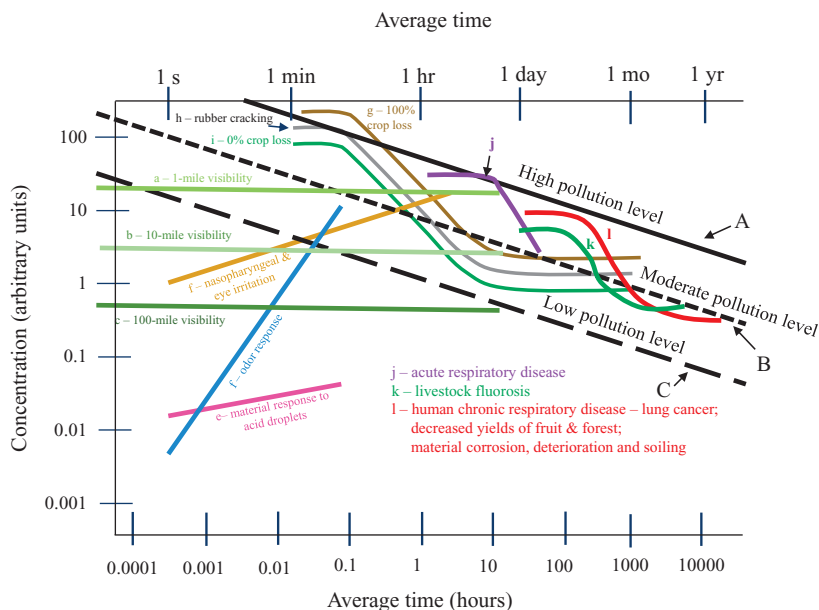


FIG. 24.1 Adverse responses to various pollution levels. Source: A.C. Stern, R. Boubel, Turner, and DB, Fox, Donald L, in: *Fundamentals of Air Pollution*, 1984.

illustrates the relationship between these concentration levels. This figure displays response curves, which remain on the concentration duration axes because they are characteristic of the receptors, not of the actual air quality to which the receptors are exposed. The odor response curve, for example, to hydrogen sulfide, shows

that an inhalation event of one second can establish the presence of the odor but that, due to odor fatigue, the ability to continue to recognize that odor can be lost in a matter of minutes. Nasopharyngeal and eye irritation, for example, by ozone, is similarly subject to acclimatization due to tear and mucus production. The three

visibility lines correlate with the concentration of suspended particulate matter in the air. Attack of metal, painted surfaces, or nylon hose is shown by a line starting at one second and terminating in a matter of minutes, when the acidity of the droplet is depleted by the material attacked.

Plant damage can be measured biologically or socioeconomically. Biological damage can be measured as stress on growth and survival. Socioeconomic damage can be measured as 0% loss when there is no loss of the sale value of the crops or ornamental plants but a 100% loss if the crop is damaged to the extent that it cannot be sold. Such responses are related to dose, that is, concentration times duration of exposure, as shown by the percent loss curves on the chart. Many manifestations of material damage, for example, rubber cracking by ozone, require an exposure duration long enough for the adverse effects to be economically significant. That is, attack for just a few seconds or minutes will not affect the utility of the material for its intended use, but attack for several days will.

The biological response line for acute respiratory disease is a dose-response curve which for a constant concentration becomes a duration-response curve.

The shape of such a curve reflects the ability of the human body to cope with short-term, ambient concentration respiratory exposures and the overwhelming of the body's defenses by continued exposure. For example, fluorosis of livestock is not induced until there has been a long enough period of deposition of a high enough ambient concentration of fluoride to increase the level of fluoride in the forage. Since the forage is either consumed by livestock or cut for hay at least once during the growing season, the duration of deposition ends after the growing season. The greater the duration of the season, the greater the time for deposition, hence the shape of the line labeled "fluorosis." Long-term vegetation responses—decreased yield of fruit and forest—and long-term material

responses—corrosion, soiling, and material deterioration—are shown on the chart as having essentially the same response characteristics as human chronic respiratory disease and lung cancer.

The relationship of these response curves to ambient air quality is shown by lines A, B, and C, which represent the maximum or any other chosen percentile line from a display such as [Fig. 24.1](#), which shows actual air quality. Where the air quality is poor (line A), essentially all the adverse effects displayed will occur. Where the air quality is good (line C), most of the intermediate- and long-term adverse effects displayed will not occur. Where the air quality is between good and poor, some of the intermediate- and long-term adverse effects will occur, but in an attenuated form compared with those of poor air quality.

4.1 Air Quality Indices

Air quality indexes (AQIs) categorize the air quality measurements of several individual pollutants by one composite number. The index described in [Table 24.3](#) is used by the U.S. EPA, as authorized by Section 319 of the Clean Air Act. Comparable values for international standards are shown in [Table 24.4](#).

The air quality index (AQI) was developed for five air pollutants: particulate matter (PM), ground-level ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). The AQI calculates the quality of the air for each pollutant on a scale from 0 to 500. Decreasing values indicate improving air quality. However, each pollutant is reported separately, so one pollutant can be good (i.e., green) whereas another can be hazardous (i.e., maroon) at same time and place. The AQI is a piecewise linear function of the concentration of each pollutant, that is, a function of real numbers with a graph of straight line segments. For example, if a wildfire has been burning upwind of a town, with downtown measurements taken

TABLE 24.3 Air Quality Index

Air Quality Index	Who Needs to be Concerned?	What Should I Do?
Good 0–50		It's a great day to be active outside
Moderate 51–100	Some people who may be unusually sensitive to particle pollution	Unusually sensitive people: <i>Consider reducing</i> prolonged or heavy exertion. Watch for symptoms such as coughing or shortness of breath. These are signs to take it easier. Everyone else: it is a good day to be active outside
Unhealthy for sensitive groups 101–150	Sensitive groups include people with heart or lung disease, older adults, children, and teenagers	Sensitive groups: Reduce prolonged or heavy exertion. It is OK to be active outside, but take more breaks and do less intense activities. Watch for symptoms such as coughing or shortness of breath. <i>People with asthma</i> should follow their asthma action plans and keep quick relief medicine handy. If you have heart disease: Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider
Unhealthy 151–300	Everyone	Sensitive groups: <i>Avoid</i> prolonged or heavy exertion. Move activities indoors or reschedule to a time when the air quality is better. Everyone else: <i>Reduce</i> prolonged or heavy exertion. Take more breaks during all outdoor activities
Very unhealthy 201–300	Everyone	Sensitive groups: <i>Avoid all</i> physical activity outdoors. Move activities indoors or reschedule to a time when air quality is better. Everyone else: <i>Avoid</i> prolonged or heavy exertion. Consider moving activities indoors or rescheduling to a time when air quality is better
Hazardous 301–500	Everyone	Everyone: <i>Avoid all</i> physical activity outdoors. Sensitive groups: Remain indoors and keep activity levels low. Follow tips for keeping particle levels low indoors

Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999; EPA-454/B-16-002, *Technical Assistance Document for the Reporting of Daily Air Quality—the Air Quality Index (aqi)*: US Environmental Protection Agency, 2016; U.S. Environmental Protection Agency, *Air Quality Index (AQI) Basics*, 2016. Available from: <https://www.airnow.gov/index.cfm?action=aqibasics.aqi>.

fine particles, that is, PM with a diameter $\leq 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$), found to average 22 micrograms per cubic meter ($\mu\text{g m}^{-3}$) for the last 24h. The AQI category, that is, the index value (I), can be found as a linear function:

$$I = \frac{I_{\text{high}} - I_{\text{low}}}{C_{\text{high}} - C_{\text{low}}} \times (C - C_{\text{low}}) + I_{\text{low}} \quad (24.3)$$

where, C = pollutant concentration;
 C_{low} = concentration breakpoint $\leq C$;
 C_{high} = concentration breakpoint $\geq C$; I_{low} = index breakpoint corresponding to C_{low} ; and
 I_{high} = index breakpoint corresponding to C_{high} .

Table 24.5 presents the breakpoints for the AQI pollutants.

Table 24.5 presents that $22 \mu\text{g m}^{-3}$ falls within the moderate category. Inserting these values into Eq. (24.3) gives:

$$I = \frac{100 - 51}{35.4 - 12.1} \times (22 - 12.1) + 51 \cong 72$$

Thus the fires seem to be lowering the air quality, but there is still about 28 AQI points before $\text{PM}_{2.5}$ concentrations are unhealthy for sensitive groups, like those with asthma or babies.

The precautionary statements for the NAAQS pollutants are presented in Table 24.6.

TABLE 24.4 International Air Quality Indices

WHO Air Quality Guidelines (AQGs) for Particulate Matter, Ozone, Nitrogen Dioxide, and Sulfur Dioxide			
	PM₁₀ ($\mu\text{g m}^{-3}$)	PM_{2.5} ($\mu\text{g m}^{-3}$)	Basis for the selected level
Interim target-1 (IT-1)	70	35	These levels are associated with about a 15% higher long-term mortality risk relative to the AQG level
Interim target-2 (IT-2)	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% (2%–11%) relative to the IT-1 level
Interim target-3 (IT-3)	30	15	In addition to other health benefits, these levels reduce the mortality risk by approximately 6% (2%–11%) relative to the IT-2 level
AQG	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with >95% confidence in response to long-term exposure to PM _{2.5}

WHO AQGs and interim targets for particulate matter^a: 24-h concentrations^b

	PM₁₀ ($\mu\text{g m}^{-3}$)	PM_{2.5} ($\mu\text{g m}^{-3}$)	Basis for the selected level
Interim target-1 (IT-1)	150	75	Based on published risk coefficients from multicenter studies and metaanalyses (about 5% increase of short-term mortality over the AQG value)
Interim target-2 (IT-2)	100	50	Based on published risk coefficients from multicenter studies and meta-analyses (about 2.5% increase of short-term mortality over the AQG value)
Interim target-3 (IT-3) ^c	75	37.5	Based on published risk coefficients from multicenter studies and meta-analyses (about 1.2% increase in short-term mortality over the AQG value)
AQG	50	25	Based on relationship between 24-h and annual PM levels

WHO AQG and interim target for ozone: 8-h concentrations

	Daily maximum 8-h mean ($\mu\text{g m}^{-3}$)	Basis for the selected level
High levels	240	Significant health effects; substantial proportion of vulnerable populations affected
Interim target-1 (IT-1)	160	Important health effects; does not provide adequate protection of public health. Exposure to this level of ozone is associated with: • Physiological and inflammatory lung effects in healthy exercising young adults exposed for periods of 6.6h • Health effects in children (based on various summer camp studies in which children were exposed to ambient ozone levels) • An estimated 3%–5% increase in daily mortality^d (based on findings of daily time-series studies)
AQG	100	Provide adequate protection of public health, though some health effects may occur below this level. Exposure to this level of ozone is associated with: • An estimated 1%–2% increase in daily mortality^d (based on findings of daily time-series studies) • Extrapolation from chamber and field studies based on the likelihood that real-life exposure tends to be repetitive and chamber studies exclude highly sensitive or clinically compromised subjects, or children • Likelihood that ambient ozone is a marker for related oxidants

Continued

TABLE 24.4 International Air Quality Indices—cont'd

WHO Air Quality Guidelines (AQGs) for Particulate Matter, Ozone, Nitrogen Dioxide, and Sulfur Dioxide			
	PM ₁₀ ($\mu\text{g m}^{-3}$)	PM _{2.5} ($\mu\text{g m}^{-3}$)	Basis for the selected level
WHO AQGs for nitrogen dioxide: annual mean			
	Annual mean ($\mu\text{g m}^{-3}$)		
AQG	40		Recent indoor studies have provided evidence of effects on respiratory symptoms among infants at NO ₂ concentrations below 40 $\mu\text{g m}^{-3}$. These associations cannot be completely explained by coexposure to PM, but it has been suggested that other components in the mixture (such as organic carbon and nitrous acid vapor) might explain part of the observed association
WHO AQGs for nitrogen dioxide 1-h mean			
	1-h mean ($\mu\text{g m}^{-3}$)		
AQG	200		Epidemiological studies have shown that bronchitic symptoms of asthmatic children increase in association with annual NO ₂ concentration, and that reduced lung function growth in children is linked to elevated NO ₂ concentrations within communities already at current North American and European urban ambient air levels. A number of recently published studies have demonstrated that NO ₂ can have a higher spatial variation than other traffic-related air pollutants, for example, particle mass. These studies also found adverse effects on the health of children living in metropolitan areas characterized by higher levels of NO ₂ even in cases where the overall city-wide NO ₂ level was fairly low. Since the existing WHO AQG short-term NO ₂ guideline value of 200 $\mu\text{g m}^{-3}$ (1-h) has not been challenged by more recent studies, it is retained
WHO AQGs and interim targets for SO₂: 24-h and 10-min concentrations			
	24-h average ($\mu\text{g m}^{-3}$)	10-min average ($\mu\text{g m}^{-3}$)	Basis for the selected level
Interim target-1 (IT-1) ^a	125	—	
Interim target-2 (IT-2)	50	—	Intermediate goal based on controlling either motor vehicle emissions, industrial emissions, and/or emissions from power production. This would be a reasonable and feasible goal for some developing countries (it could be achieved within a few years) which would lead to significant health improvements that, in turn, would justify further improvements (such as aiming for the AQG value)
AQG	20	500	

^a The use of PM_{2.5} guideline value is preferred.

^b 99th percentile (3 days per year).

^c For management purposes. Based on annual average guideline values precise number to be determined on basis of local frequency distribution of daily means. The frequency distribution of daily PM_{2.5} or PM₁₀ values usually approximates to a log-normal distribution.

^d Deaths attributable to ozone. Time-series studies indicate an increase in daily mortality in the range of 0.3%–0.5% for every 10 $\mu\text{g m}^{-3}$ increment in 8-h ozone concentrations above an estimated baseline level of 70 $\mu\text{g m}^{-3}$.

^e Formerly the WHO Air Quality Guideline [9].

Sources: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999; World Health Organization, *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide; Global Update 2005, 2006* (SDE/PHE/EH/06.02).

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TABLE 24.5 Breakouts for Air Quality Index (AQI)

These Breakpoints...							... Equal This AQI	... and This Category
O ₃ (ppm) 8-h ^a	O ₃ (ppm) 1-h ^b	PM _{2.5} (µg m ⁻³) 24-h	PM ₁₀ (µg m ⁻³) 24-h	CO (ppm) 8-h	SO ₂ (ppb) 1-h	NO ₂ (ppb) 1-h	AQI	
0.000–0.054	–	0.0–12.0	0–54	0.0–4.4	0–35	0–53	0–50	Good
0.055–0.070	–	12.1–35.4	55–154	4.5–9.4	36–75	54–100	51–100	Moderate
0.071–0.085	0.125–0.164	35.5–55.4	155–254	9.5–12.4	76–185	101–360	101–150	Unhealthy for sensitive groups
0.086–0.105	0.165–0.204	(55.5–150.4) ^c	255–354	12.5–15.4	(186–304) ^d	361–649	151–200	Unhealthy
0.106–0.200	0.205–0.404	(150.5–(250.4) ^c	355–424	15.5–30.4	(305–604) ^d	650–1249	201–300	Very unhealthy
See note ^e	0.405–0.504	(250.5–350.4) ^c	425–504	30.5–40.4	(605–804) ^d	1250–1649	301–400	Hazardous
See notes ^b	0.505–0.604	(350.5–500.4) ^c	505–604	40.5–50.4	(805–1004) ^d	1650–2049	401–500	Hazardous

^a 8-h O₃ values do not define higher AQI values (≥301). AQI values of 301 or higher are calculated with 1-h O₃ concentrations.

^b Areas are generally required to report the AQI based on 8-h ozone values. However, there are a small number of areas where an AQI based on 1-h ozone values would be more precautionary. In these cases, in addition to calculating the 8-h ozone index value, the 1-h ozone value may be calculated, and the maximum of the two values reported.

^c If a different SHL for PM_{2.5} is promulgated, these numbers will change accordingly.

^d 1-h SO₂ values do not define higher AQI values (≥200). AQI values of 200 or greater are calculated with 24-h SO₂ concentrations. Source: EPA-454/B-16-002, Technical Assistance Document for the Reporting of Daily Air Quality-the Air Quality Index (aqi): US Environmental Protection Agency, 2016.

FOR REFERENCE PURPOSES ONLY

TABLE 24.6 Cautionary Statements for Criteria Air Pollutants in the United States

Index Values	Levels of Health Concern	Cautionary Statements ^a			
		Ozone	Particulate Matter	Carbon Monoxide	Sulfur Dioxide
0–50	Good	None	None	None	None
51–100 ^a	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion outdoors	Unusually sensitive people should consider reducing prolonged or heavy exertion	None	People with asthma should consider reducing exertion outdoors
101–150	Unhealthy for sensitive groups	Active children and adults, and people with lung disease, such as asthma, should reduce prolonged or heavy exertion outdoors	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion	People with heart disease, such as angina, should reduce heavy exertion and avoid sources of CO, such as heavy traffic	Children, asthmatics, and people with heart or lung disease should reduce exertion outdoors
151–200	Unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid prolonged or heavy exertion outdoors. Everyone else, especially children, should reduce prolonged or heavy exertion outdoors	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion	People with heart disease, such as angina, should reduce moderate exertion and avoid sources of CO, such as heavy traffic	Children, asthmatics, and people with heart or lung disease should avoid outdoors exertion. Everyone else should reduce exertion outdoors
201–300	Very unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid all outdoor exertion. Everyone else, especially children, should avoid prolonged or heavy exertion outdoors	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion	People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic	Children, asthmatics, and people with heart or lung disease should remain indoors. Everyone else should avoid exertion outdoors
301–500	Hazardous	Everyone should avoid all physical activity outdoors	People with heart or lung disease, older adults, and children should remain indoors and keep activity levels low. Everyone else should avoid all physical activity outdoors	People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic. Everyone else should reduce heavy exertion	

^a Nitrogen dioxide can cause respiratory problems in children and adults who have respiratory diseases, such as asthma. The AQI for nitrogen dioxide is not included here because ambient nitrogen dioxide concentrations in the United States have been below the national air quality standard for the past several years. These concentrations are sufficiently low so as to pose little direct threat to human health. Nitrogen dioxide, however, is a concern because it plays a significant role in the formation of tropospheric ozone, particulate matter, haze, and acid rain. As concentrations increase, the proportion of people prone to experience health effects and the seriousness of these effects are expected to increase. Thus the 1997 standards were intended to include an ample margin of safety (as required by Section 106(b) of the Clean Air Act Amendments. The margin includes special concern about protecting the health of sensitive individuals. However, they were not considered risk free and exposures to ambient concentrations just below the numerical level of the standards may be problematic for the most sensitive individuals. On the other hand, exposures to levels just above the NAAQS are not expected to be associated with health concerns for most healthy individuals. Such is the complicated nature of individual response to air pollutants, and one of the objectives of the revised index is to provide sufficient information to allow sensitive people to avoid unhealthy exposures.

Source: D. Mintz, *Guidelines for the Reporting of Daily Air Quality—Air Quality Index (AQI)*, US Environmental Protection Agency, Research Triangle Park, 2006.

5 AIR POLLUTION CONTROL

Air pollution control must be strategic and tactical. The former is the long-term reduction of pollution levels at all scales of the problem from local to global. Goals can be set for air quality improvement 5, 10, or 15 years ahead and plans made to achieve these improvements.

5.1 Strategies

One notable example is the requirement of the CAAA of 1990 to reduce the emissions of hazardous air pollutants (so-called “HAPs”). The law requires the EPA to establish an inventory to track progress in reducing HAPs in ambient air. The first step of this strategy [4] was to promulgate technology-based emission standards (maximum achievable control technology, i.e., MACT). For major sources of HAPs, Section 112(f) requires standards to address risks remaining after implementation of MACT standards, known as residual risks standards. Section 112(c)(3) and Section 112(k) of the CAAA require EPA to address the emissions and risks of HAPs from area sources and to show a 75% reduction in cancer incidence of emissions from stationary sources of HAPs since 1990. To monitor the success in meeting these strategies in reducing emissions and human health, EPA compiles the National Emissions Inventory (NEI) for HAPs. The EPA previously compiled a baseline 1990 and 1996 National Toxics Inventory (NTI) and 1999 NEI for HAPs and has recently completed version 3 of the 2002 NEI.

The NEI includes major point and area sources, nonpoint area and other sources, and mobile source estimates of emissions. Stationary major sources of HAPs are defined as sources that have the potential to emit 9 t per annum (9 t a^{-1} or 10 US tons per annum) or more of any single HAP or 22.7 t a^{-1} (25 US tons per year) or more of any combination of HAPs [10]. Stationary area sources of HAPs are defined as sources that have the potential to emit $<9 \text{ t a}^{-1}$ or more of any single

HAP or $<22.7 \text{ t a}^{-1}$ or more of any combination of HAPs. Mobile sources include onroad vehicles, nonroad equipment, and aircraft/locomotive/commercial marine vessels (ALM). EPA has developed the National Air Toxics Assessment (NATA) to estimate the magnitude of HAP emissions reductions and demonstrate reduced public risk from HAP emissions attributable to CAA toxics programs [10].

Emissions of HAPs fell through the 1990s in response to the MACT standards and mobile source regulations. However, area and other source emissions have increased because the EPA has not yet fully implemented its area source program as required by Section 112(c)(3) and 112(k) of the CAAA. Fig. 24.2 and Table 24.7 present emissions trends for the sum of 188 HAPs by source sectors. Toxicity-weighted emissions have also declined between 1990 and 2002 for cancer and noncancer respiratory and neurological effects. Figs. 24.3–24.5 and Tables 24.8–24.10 provide the toxicity-weighted emissions scaled to the sum of $6.57 \times 10^6 \text{ t}$ (7.24 million US tons) for 1990 total emissions.

In 2002 benzene accounts for 28% of cancer risks in the toxicity-weighted NEI, whereas manganese accounts for 77% of noncancer

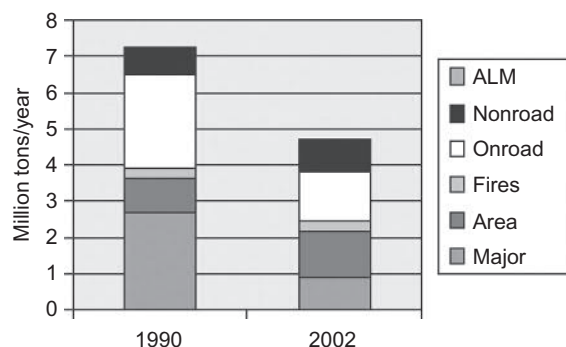


FIG. 24.2 Trends in US emissions of hazardous air pollutants. Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

TABLE 24.7 Sum of Emissions of the 188 Hazardous Air Pollutants Listed in the Clean Air Act Amendments of 1990

Sector	1990 Emissions	2002 Emissions	% Reduction
Total	7.24 million tons	4.7 million tons	35
Major	2.69 million tons	0.89 million tons	67
Area	0.91 million tons	1.29 million tons	-42
Fires (wildfires and prescribed burns)	0.34 million tons	0.28 million tons	18
Onroad mobile	2.55 million tons	1.36 million tons	47
Nonroad Mobile	0.75 million tons ^a	0.86 million tons	-15
ALM Mobile ^b		0.02 million tons	

Here ton refers to a short ton (US) which is equivalent to 907 kg.

^a 1990 Nonroad mobile includes ALM.

^b ALM: aircraft locomotive and commercial marine vessels.

Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

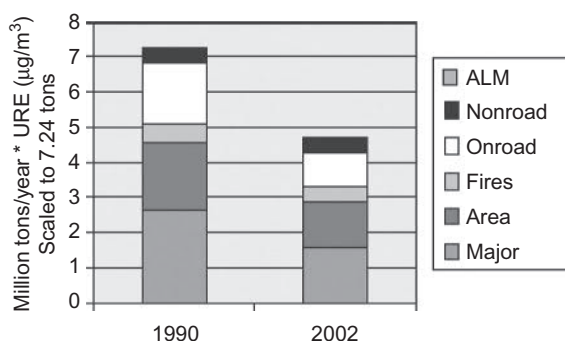


FIG. 24.3 Trends in scaled cancer toxicity-weighted US emissions of hazardous air pollutants. *Note:* Unit risk estimate (URE) is upper bound risk estimate of an individual's probability of contracting cancer over a lifetime of exposure to a concentration of $1\mu\text{g}$ of the pollutant per cubic meter of air. For example, if an URE is $1.5 \times 10^{-6} \mu\text{g}^{-1} \text{m}^{-3}$, 1.5 excess tumors are expected to develop per 1,000,000 people if they are exposed daily for a lifetime to $1\mu\text{g}$ of the pollutant in 1 cubic meter of air. Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

neurological effects in the toxicity-weighted NEI, and acrolein accounts for 90% of non-cancer respiratory effects in the toxicity-weighted NEI [10].

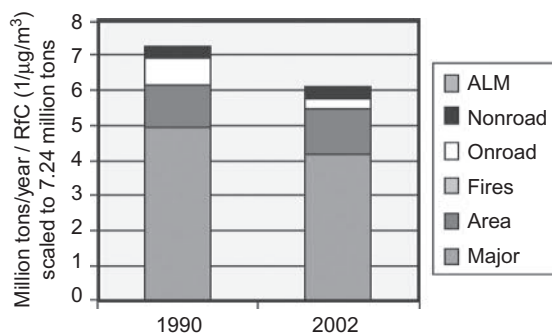


FIG. 24.4 Trends in scaled noncancer neurological toxicity-weighted US emissions of hazardous air pollutants. *Note:* RfC is the reference concentration, that is, the concentration, based on the no-adverse effect concentration and uncertainties, below which no adverse effect is expected. Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

A regional strategy can affect planned reductions at the urban and local scales, as well as a state or provincial strategy to achieve reductions at the state, provincial, urban, and local scales; and a national strategy to achieve them at national and lesser scales. The continental and global

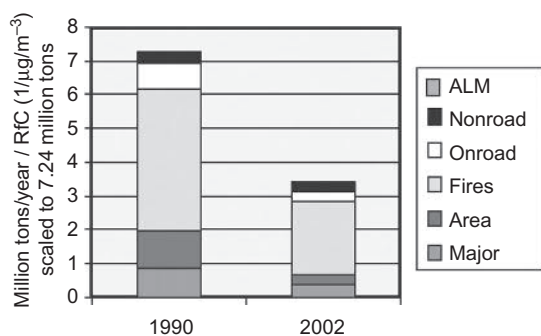


FIG. 24.5 Trends in scaled noncancer respiratory toxicity-weighted US emissions of hazardous air pollutants. *Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.*

TABLE 24.8 Trends in Scaled Cancer Toxicity-Weighted US Emissions of Hazardous Air Pollutants

Sector	% Reduction From 1990 to 2002
Total	36
Major	44
Area	31
Fires (wildfires and prescribed burns)	–4
Onroad mobile	49
Nonroad mobile	7.5

Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

scales require an international strategy for which an effective instrumentality is being developed.

5.2 Tactics

Urban areas experience short-term episodes of elevated concentrations of air pollutants. Prior to an episode, a scenario of tactical

TABLE 24.9 Trends in Scaled Noncancer Neurological Toxicity-Weighted US Emissions of HAPs

Sector	% Reduction From 1990 to 2002
Total	16
Major	15
Area	–7
Fires (wildfires and prescribed burns)	0
Onroad mobile	62
Nonroad mobile	12

Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

TABLE 24.10 Trends in Scaled Noncancer Respiratory Toxicity-weighted US Emissions of hazardous air pollutants

Sector	% Reduction From 1990 to 2002
Total	54
Major	69
Area	64
Fires (wildfires and prescribed burns)	50
Onroad mobile	58
Nonroad mobile	35

Source: A. Pope, M. Strum, 1990–2002 NEI HAP Trends: Success of CAA Air Toxic Programs in Reducing HAP Emissions and Risk, in: 16th Annual International Emission Inventory Conference—Emission Inventories: “Integration, Analysis, and Communications”, Raleigh, NC, 2006.

maneuvers must be developed for application on very short notice to prevent an impending episode from becoming a disaster. Since an episode usually varies from a minimum of about 36 h to a maximum of 3 or 4 days, temporary controls on emissions much more severe than are called for by the long-term strategic control scenario must be implemented rapidly and maintained for the

duration of the episode. After the weather conditions that gave rise to the episode have passed, these temporary episode controls can be relaxed and controls can revert to those required for long-term strategic control [11].

The mechanisms by which a jurisdiction develops its air pollution control strategies and episode control tactics are outlined in Fig. 24.6. Most of the boxes in the figure have already been discussed—sources, pollutant emitted, transport and diffusion, atmospheric chemistry, pollutant half-life, air quality, and air pollution effects. To complete an analysis of the elements of the air pollution system, it is necessary to explain the several boxes not yet discussed.

5.3 Episodes

The distinguishing feature of an air pollution episode is its persistence for several days, allowing continued buildup of pollution levels. Consider the situation of the air pollution control

officer who is expected to decide when to use the stringent control restrictions required by the episode control tactics scenario (Fig. 24.7 and Table 24.11). If these restrictions are imposed and the episode does not mature, that is, the weather improves and blows away the pollution without allowing it to accumulate for another 24h or more, the officer will have required a very large expenditure by the community and a serious disruption of the community's normal activities. Also, part of the officer's credibility in the community will be diminished and weakens the urgency when a real episode occurs. If, however, the reverse situation occurs—that is, the restrictions are not invoked and an episode does occur—there can be illness or possibly deaths in the community that could have been averted.

In deciding whether or not to initiate episode emergency plans, the control officer cannot rely solely on measurements from air quality monitoring stations, because even if pollutant concentrations rise toward acute levels over the preceding hours, these readings give no

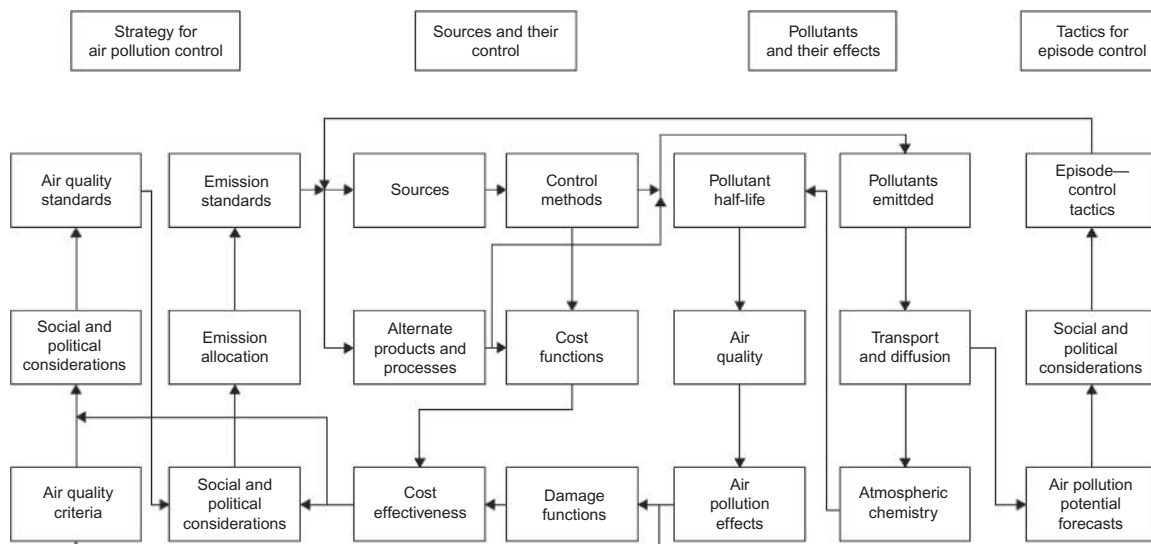


FIG. 24.6 Model of the air pollution management system. Source: A.C. Stern, R. Boubel, Turner, and DB, Fox, Donald L, in: *Fundamentals of Air Pollution*, 1984.

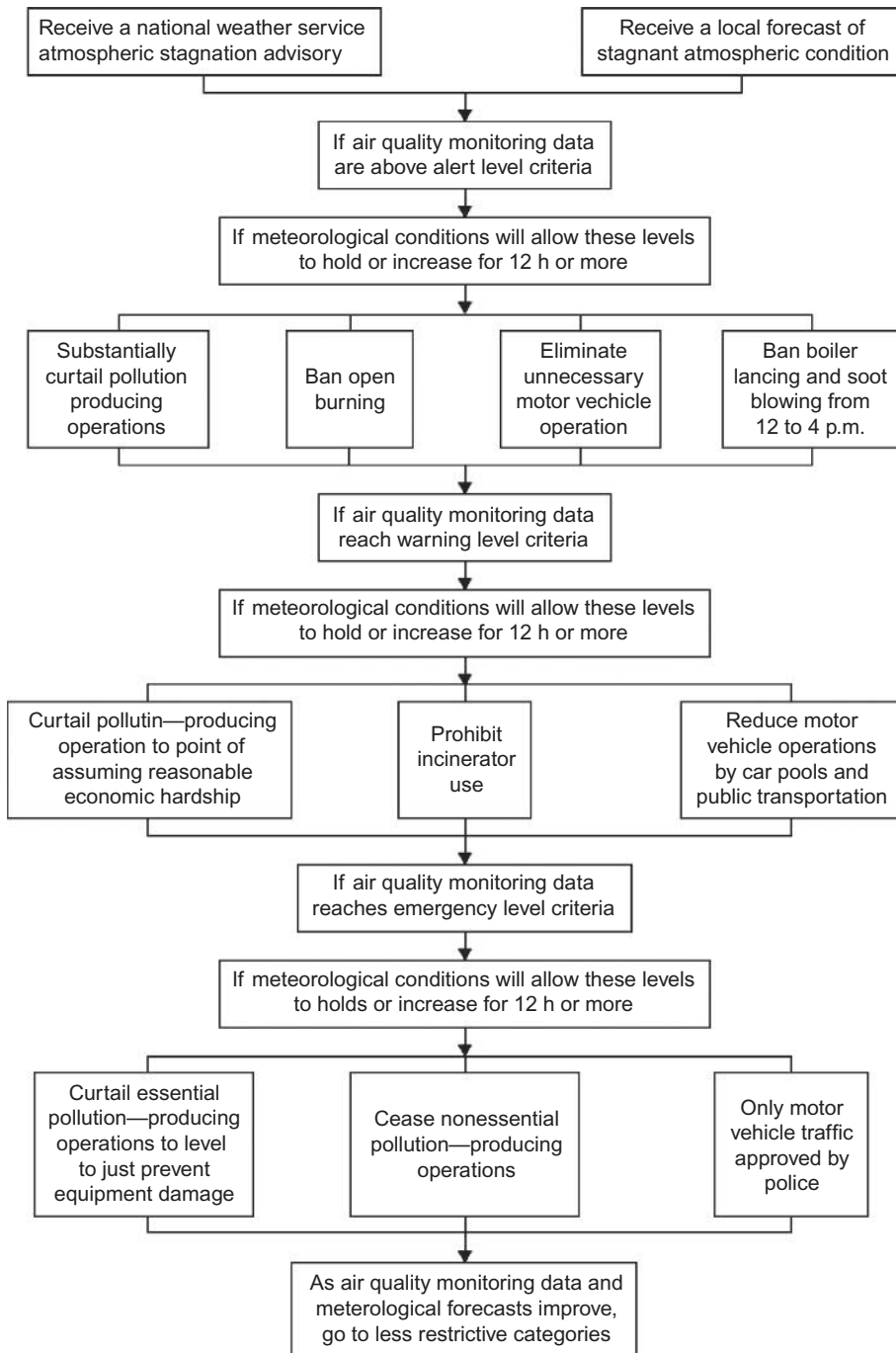


FIG. 24.7 Air pollution episode control scenario. See [Table 24.11](#). Source: A.C. Stern, R. Boubel, Turner, and DB, Fox, Donald L, in: *Fundamentals of Air Pollution*, 1984.

TABLE 24.11 United States Alert, Warning, and Emergency Level Criteria^{a-c}*Alert level criteria*SO₂800 $\mu\text{g m}^{-3}$ (0.3 ppm), 24-h averagePM₁₀350 $\mu\text{g m}^{-3}$, 24-h average

CO

17 mg m^{-3} (15 ppm), 8-h average

Ozone

400 $\mu\text{g m}^{-3}$ (0.2 ppm), 1-h averageNO₂1130 $\mu\text{g m}^{-3}$ (0.6 ppm), 1-h average; 282 $\mu\text{g m}^{-3}$ (0.15 ppm), 24-h average*Warning level criteria*SO₂1600 $\mu\text{g m}^{-3}$ (0.6 ppm), 24-h averagePM₁₀420 $\mu\text{g m}^{-3}$, 24-h average

CO

34 mg m^{-3} (30 ppm), 8-h average

Ozone

800 $\mu\text{g m}^{-3}$ (0.4 ppm), 1-h averageNO₂2260 $\mu\text{g m}^{-3}$ (1.2 ppm), 1-h average; 565 $\mu\text{g m}^{-3}$ (0.15 ppm), 24-h average*Emergency level criteria*SO₂2100 $\mu\text{g m}^{-3}$ (0.8 ppm), 24-h averagePM₁₀500 $\mu\text{g m}^{-3}$, 24-h average

CO

46 mg m^{-3} (15 ppm), 8-h average

Ozone

1000 $\mu\text{g m}^{-3}$ (0.1 ppm), 1-h averageNO₂3000 $\mu\text{g m}^{-3}$ (0.6 ppm), 1-h average; 750 $\mu\text{g m}^{-3}$ (0.15 ppm), 24-h average

^a 2003 Code of Federal Regulations, Title 40-Protection of Environment, Chapter 1—Environmental Protection Agency, Appendix L, Example Regulations for Prevention of Air Pollution Emergency Episodes, 1.1 Episode Criteria, pp., 351–352.

^b There is no criterion for lead due to the chronic nature of the health effects of concern.

^c Note: Append to each entry: Meteorological conditions are such that pollutant concentrations can be expected to remain at the above levels for 12 or more hours or increase, or in the case of ozone the situation is likely to reoccur within the next 24 h unless control actions are taken.

Sources: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999; A.C. Stern, R. Boubel, Turner, and DB, Fox, Donald L, in: *Fundamentals of Air Pollution*, 1984.

information on whether they will rise or fall during the succeeding hours [11].

The only way to avert this dilemma is for the community to develop and utilize its capability of forecasting the advent and persistence of the stagnation conditions during which an episode occurs and its capability of computing pollution concentration buildup under stagnation conditions. Social and political considerations provide a point in the flow chart for the public debates, hearings, and action processes necessary to decide, well in advance of an episode, what control tactics to use and when to call an end to the emergency. The public needs to be involved because alternatives must be written into the scenario concerning where, when, and in what order to impose restrictions on sources. This should be done in advance and should be well publicized, because during the episode there is no time for public debate. In any systems analysis, the system must form a closed loop with feedback to keep the system under control. It will be noted that the system for tactical episode control is closed by the line connecting episode control tactics to sources, which means that the episode control tactics are to limit sources severely during the episode. Since it takes hours before emergency plans can be put into effect and their impact on pollution levels felt, it is possible that by the time the community responds, the situation has disappeared. Experience has shown that the time for community response is slowed by the need to write orders to close sources and

to respond in court to requests for judicial relief from such orders. To circumvent the former type of delay, orders can be written in blank in advance. To circumvent the latter type of delay, the agency's legal counsel must move as rapidly as the counsel seeking such relief [11].

6 AIR QUALITY MANAGEMENT

Means of controlling air pollution sources include (1) using devices to remove all or part of the pollutant from the gases discharged to the atmosphere, (2) changing the raw materials used in the pollution-producing process, or (3) modifying the operation of the process to decrease pollutants emitted. These are control methods (see Table 24.12). Such control methods have a cost associated with them and are the cost functions that appear in the system. There is always the option of seeking alternate products or processes which will provide the same utility to the public but with less quantity of pollutants emitted. Such products and processes have their own cost functions [4].

Both controlling and not controlling air pollution have costs. All the adverse air pollution

TABLE 24.12 Examples of Air Pollution Control Methods

I. Applicable to all emissions

A. Decrease or eliminate production of emission

1. Change specification of product
2. Change design of product
3. Change process temperature, pressure, or cycle
4. Change specification of materials
5. Change the product

B. Confine the emissions

1. Enclose the source of emissions
2. Capture the emissions in an industrial exhaust system
3. Prevent drafts

C. Separate the contaminant from effluent gas stream

Scrub with liquid

II. Applicable specifically to particulate matter emissions

A. Decrease or eliminate particulate matter production

1. Change to process that does not require blasting, blending, buffing, calcining^a, chipping, crushing, drilling, drying, grinding, milling, polishing, pulverizing, sanding, sawing, spraying, and tumbling, and so on

2. Change from solid to liquid or gaseous material

3. Change from dry to wet solid material

4. Change particle size of solid material

5. Change to process that does not require particulate material

B. Separate the contaminant from effluent gas stream

1. Gravity separator

2. Centrifugal separator

3. Filter

4. Electrostatic precipitator

III. Applicable specifically to gaseous emissions

A. Decrease or eliminate gas or vapor production

1. Change to process that does not require annealing, baking, boiling, burning, casting, coating, cooking, dehydrating, dipping, distilling, expelling, galvanizing, melting, pickling, plating, quenching, reducing, rendering, roasting, and smelting, and so on

2. Change from liquid or gaseous to solid material

3. Change to process that does not require gaseous or liquid material

B. Burn the contaminant to CO₂ and H₂O

1. Incinerator

2. Catalytic burner

C. Adsorb the contaminant

1. Activated carbon

2. Other sorbents

^a Calcining is the process of heating a substance to a temperature less than melting or fusing point, but sufficiently high to cause moisture loss, redox, and decomposition of carbonates and other compounds.

Source: A.C. Stern, R. Boubel, Turner, and DB, Fox, Donald L, in: *Fundamentals of Air Pollution*, 1984.

effects represent economic burdens on the public for which an attempt can be made to assign dollar values, that is, the cost to the public of damage to vegetation, materials, structures, animals, the atmosphere, and human health. These costs are called damage functions. To the extent that there is knowledge of cost functions and damage functions, the cost-effectiveness of control methods and strategies can be determined by their interrelationship. Cost-effectiveness is an estimate of how many dollars worth of damage can be averted per dollar expended for control. It gives information on how to economically optimize an attack on pollution, but it gives no information on the reduction in pollution required to achieve acceptable public health and well-being. However, when these goals can be achieved by different control alternatives, it behooves us to utilize the alternatives that show the greatest cost-effectiveness [4, 11].

Air quality data are used as the basis for determining the pollution concentrations in air that are compatible with acceptable public health and well-being, use is made of air quality criteria, which are statements of the air pollution effects associated with various air quality levels. It is inconceivable that any jurisdiction would accept levels of pollution it recognizes as damaging to health. However, the question of what constitutes damage to health is judgmental and therefore debatable. The question of what damage to well-being is acceptable is even more judgmental and debatable. Because they are debatable, the same social and political considerations come into the decision-making process as in the previously discussed case of arriving at episode control tactics. Cost-effectiveness is not a factor in the acceptability of damage to health, but it is a factor in determining acceptable damage to public well-being. Some jurisdictions may opt for a pollution level that allows some damage to vegetation, animals, materials, structures, and the atmosphere if they are assured that there will be no damage to their constituents' health. The concentration level the jurisdiction selects

by this process is called an air quality standard. This is the level the jurisdiction says it wishes to maintain [4, 11].

7 CONCLUSIONS

Waste management actions can impact air quality whenever they result in emissions. The atmosphere is a receptor of these emissions. Substantial progress has been made in improving air quality since the 1970s. The criteria pollutants in many countries have been reduced dramatically. The science, engineering, and technology needed to control the release of air pollutants have progressed, but still new ways of thinking about air pollution are needed. Economic progress has unfortunately been accompanied by seemingly intractable problems. Global greenhouse gas emissions continue to rise. Numerous toxic compounds continue to be released. Risks to human health persist. Sensitive ecosystems are threatened. Certainly, improved technologies and better regulations have resulted in cleaner air, but these emergent problems are not readily resolved by the old "command and control" approaches. Innovations and market forces must also be part of the solution, as must life cycle, preventive and sustainable processes. Indeed, improved waste management approaches will translate into improved air quality.

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Waste Electrical and Electronic Equipment

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1 INTRODUCTION

Households and offices, today, are increasingly being equipped with appliances which either have a plug or a battery. These gadgets facilitate our lives, make our work better and easier, assist in faster communication and transport, and also protect us from harm. Nevertheless, these products do not come without reserve: although the production of high-tech equipment is often associated with sterile

laboratories, the equipment very often contains significant amounts of extremely scarce, sometimes hazardous and very often valuable, material. Furthermore in operation mode, electrical and electronic equipment consumes energy which might very well come from fossil and other nonsustainable sources. At the “end-of-life,” much of the waste from these products is neither collected nor appropriately treated, which results in environmental pollution and a loss of vital metals and possibly health hazards

in one form or another. There is a wide gulf between our enjoyment of modern technological equipment and the sustainable use of the precious elements and materials that make up the equipment.

This article is mainly concerned with the end-of-life stage of electrical and electronic equipment (EEE): the so-called E-waste. No attempt has been made to include details of the treatment of E-waste that can be found in Ref. [1].

2 WHAT IS E-WASTE?

Legal and policy texts around the globe have introduced hundreds of definitions of E-waste in order to assign responsibilities linked to the necessary financing of “take-back” schemes and the financing of recovery treatment processes. The motivation behind some of the definitions becomes obvious when certain electrical components are not included, such as E-waste from the automotive industry. This is unrealistic as the only difference between the automotive E-waste and other electrical equipment waste is that the automotive E-waste is a component in an automobile. Furthermore, batteries as direct energy suppliers are also legally not included in many definitions of E-waste, though the end-of-life treatment is quite similar to other E-waste components.

The most pragmatic definition provided by the international initiative “Solving the E-waste problem” (StEP) is:

“E-waste is a term used to cover all items of electrical and electronic equipment (EEE) and its parts that have been discarded by its owner as waste without the intent to re-use” [2].

E-waste covers six waste categories (see Fig. 25.1):

1. Temperature exchange equipment, more commonly referred to as cooling and freezing equipment. Typical equipment includes

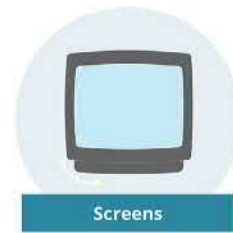
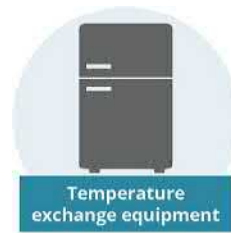


FIG. 25.1 What is E-waste? [3].

refrigerators, freezers, air conditioners, heat pumps.

2. Screens, monitors. Typical equipment includes televisions, monitors, laptops, notebooks, and tablets.
3. Lamps. Typical equipment includes fluorescent lamps, high intensity discharge lamps, and LED lamps.
4. Large equipment. Typical equipment includes washing machines, clothes dryers, dish-washing machines, electric stoves, large printing machines, copying equipment, and photovoltaic panels.

5. Small equipment. Typical equipment includes vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring and control instruments.
6. Small IT and telecommunication equipment. Typical equipment includes mobile phones, Global Positioning Systems (GPS), pocket calculators, routers, personal computers, printers, telephones [3].

The original function of each category makes for differences in each category. These include weight, size, and material composition as well as the life span. Furthermore, between the categories there are differences in the quantity and quality of E-waste, resulting in varying economic values and potential environmental and health impacts through inappropriate material recycling. Consequently, the collection and logistical processes involved and the recycling technology differ for each category, in the same way as consumer attitudes vary, when disposing of electrical and electronic equipment.

These differences contributed to the fact that some national jurisdictions do not cover all six categories. For example, in most States of the United States, large household appliances do not fall under E-waste at all. This makes the quantification of global E-waste a challenge, as it is sometimes difficult to obtain reliable national figures of the amounts of the different categories involved.

3 HOW MUCH EEE AND E-WASTE?

Researchers working on the European Commission (EC) funded the waste project "Prospecting secondary raw materials in the urban mine and mining" (ProSUM) calculated that if all of the electrical equipment in stock

in households, businesses, and public space were shared among each inhabitant of all EU member state plus Switzerland and Norway, each person would own close to 44 EEE products plus another 12 (energy saving) lamps and 33 light fittings. In addition, the researchers included 0.50 vehicles per person and taking the vehicles, electronic equipment, and other applications into account, calculated that that each person would also own 40 batteries [4].

The Global E-waste Monitor 2017, a collaborative effort of the United Nations University (UNU), represented through its Vice-Rectorate in Europe Sustainable Cycles (SCYCLE) Programme, the International Telecommunication Union (ITU), and the International Solid Waste Association (ISWA), noted that as a result of the rapidly expanding mobile-cellular and broadband networks and services, worldwide, more people especially in rural and previously unconnected areas have access to the Internet and:

- Some 3.6 billion people—close to half the world's population—are using the Internet,
- It is estimated that, worldwide, there are 7.7×10^9 (7.7 billion) mobile-cellular subscriptions and 4.2×10^9 active mobile broadband subscriptions,
- Over 80% of the world's population is covered by a mobile broadband signal [3].

The sale of EEE, in general, has shown rapid growth over the period from 2000 to 2016. UNU estimates that worldwide, countries with purchasing power parity (PPP) between US\$ 2000 and US\$ 7000 per inhabitant per year show the highest annual growth rates. The sales in terms of mass of EEE grow at a rate of 23% annually. The growth rates progressively decline to just 1.6% for the richest countries in the world, but for countries with the lowest PPP the growth rate is 15% per year [3]. This indicates that the emerging economies with a lowish PPP show the fastest annual growth rates in EEE consumption. In consequence one can conclude that the

growing middle class in countries with economies in transition contribute substantially to the increasing usage of EEE and unfortunately, also to an ever growing mountain of E-waste.

The products that had the largest absolute growth of consumption in terms of mass were fridges, washing machines, electric furnaces, electric centralized heating units, and flat panel TVs. The demand for EEE goods, which for many people represent a higher standard of living, is expected to increase.

Over the same time period, some technologies have become obsolete. The largest declines in sales were found for portable audios, portable videos, bulky cathode ray tube (CRT) monitors, and CRT televisions. These technologies are being replaced by new technologies; a particular case is the shift from CRT monitors to flat panel displays. In other cases a single device with single functionality is being replaced by items with multiple functions, such as mobile phones or laptops [3].

Key factors for the success and spread of EEE and the Internet include a high degree of competition in the telecommunication market, technological advances, particularly in computing power and mobile broadband technologies, and decreases in the price of services and devices. Additional trends that are driving the generation of E-waste include growing multiple device ownership, the tendency to electrify items that previously were nonelectrical, such as clothes and toys, growth in cloud computing services, a growing number of data centers, shorter replacement cycles of many EEE categories due to lower product quality, designs not supporting repair and refurbishment, and finally the consumers' interest in keeping up with technological changes.

All this results in an ever growing mountain of E-waste. It has been reported by UNU, ITU, and ISWA that the global quantity of E-waste generation in 2016 was around 44.7 Mt (44.7 million metric tonnes), or 6.1 kg per inhabitant. It is estimated that in 2017, the world E-waste

generation will exceed 46Mt. The amount of E-waste is expected to grow to 52.2Mt in 2021, with an annual growth rate of 3%–4%.

The global quantity of E-waste in 2016 is mainly made up of small equipment (16.8Mt), large equipment (9.2Mt), temperature exchange equipment (7.6Mt), and screens (6.6Mt). Lamps and small IT items represent a smaller share of the global quantity of E-waste generated in 2016: 0.7Mt and 3.9Mt, respectively (see Fig. 25.2).

Of all the world regions, Asia generated the most E-waste in 2016: around 18.2Mt, or 4.2kg per inhabitant. Oceania generated the highest quantity per inhabitant: 17.3kg per inhabitant. However, Oceania generated the lowest global quantity of E-waste in 2016: 0.7Mt. The European continent, including Russia, generated an amount of E-waste per inhabitant comparable to Oceania (16.6kg per inhabitant). In total, the E-waste generation for greater Europe was 12.3Mt. The lowest amount of E-waste per inhabitant was generated in Africa: 1.9kg per inhabitant. The whole African continent generated 2.2Mt of E-waste. In 2016 the Americas generated 11.3Mt of E-waste: 7Mt for North America, 3Mt for South America, and 1.2Mt for Central America. The whole continent generated 11.6kg per inhabitant of E-waste in 2016.

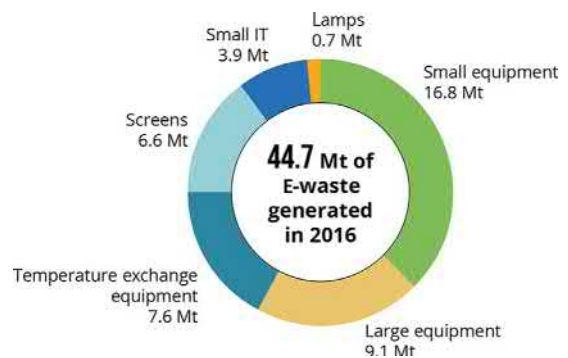


FIG. 25.2 Estimates of E-waste totals per category in 2016 [3].

4 HOW IS E-WASTE TREATED?

E-waste statistics are still limited and data is mainly derived through statistical reports in conjunction with sales data; product life span; and datasets detailing stocks, sales, and reported E-waste generation for each country. In 2016 only 8.9Mt of the total world generated E-waste of 44.7Mt was reported as being formally collected and recycled through official take-back systems. This is less than 20% of the global total. However, four scenarios illustrate how things differ under various circumstances.

4.1 Official Take-Back Systems

Countries with official take-back systems in place are early adopters in the development and enforcement of legal mechanisms to control E-waste. Often building on strong existing frameworks for solid waste management, E-waste is collected by designated organizations, producers, and/or by the government. This happens via retailers, municipal collection points, and/or pickup services. The final destination of the returned E-waste is state-of-art take-back and treatment facilities, which recover the valuable and scarce materials in an environmentally sound way. In 40 European countries including Russia, roughly 35% of the annually generated E-waste is officially reported in this manner. In the Americas, the level is around 17%, Asia 15%, Oceania 6%, and Africa 0% [3].

The scope of collected products differs among countries, depending on their national priority settings. In consequence product categories with either significant potential for resource recovery or those containing a significant amount of toxic elements are collected such as cooling and freezing equipment, screens and monitors, and small IT items.

It should be stressed that this disposal scenario exists not only in (post)industrialized countries, but also economies in transition often referred to as developing countries.

4.2 Mixed Disposal

Most of the countries that do not have specific E-waste legislation in place fall into the mixed disposal scenario. Here E-waste is either managed through voluntary public-private partnerships or simply disposed of, directly, through the normal household bins mixed up with other types of solid wastes. As such it ends up in either landfill sites or is sent to solid waste incineration plants for disposal, leading to a loss of a valuable resource. Furthermore, E-waste in landfills can lead to toxic leakages and also, without state-of-art filters, incineration might lead to substantive and toxic air emissions. Products commonly thrown away in dustbins include small equipment such as IT items and lamps.

There are no official statistics of E-waste that is disposed of with mixed residual wastes. The Countering Waste in Electrical and Electronic Equipment Illegal Trade (CWIT) project estimates that in the EU in 2012, 750kt of E-waste ended up mixed in waste bins [5]. This represents roughly 8% of the total EU E-waste generation.

This scenario exists in postindustrialized countries, but also economies in transition and in some developing countries. But in most developing countries valuable E-waste is hardly seen in household-bins.

4.3 Outside Systems

In many countries E-waste is also collected outside any official take-back systems by individual waste dealers or companies (see Fig. 25.3). Such an approach is, for example, supported by bulky waste collections, during which E-waste is placed on streets for pickup by the municipality, but precollected by waste dealers or companies and then traded through various channels. This applies especially for temperature exchange equipment, large equipment and screens/TVs, and other ICT products. In this scenario possible destination for this E-waste includes metal recycling, plastics recycling, and exports. However,

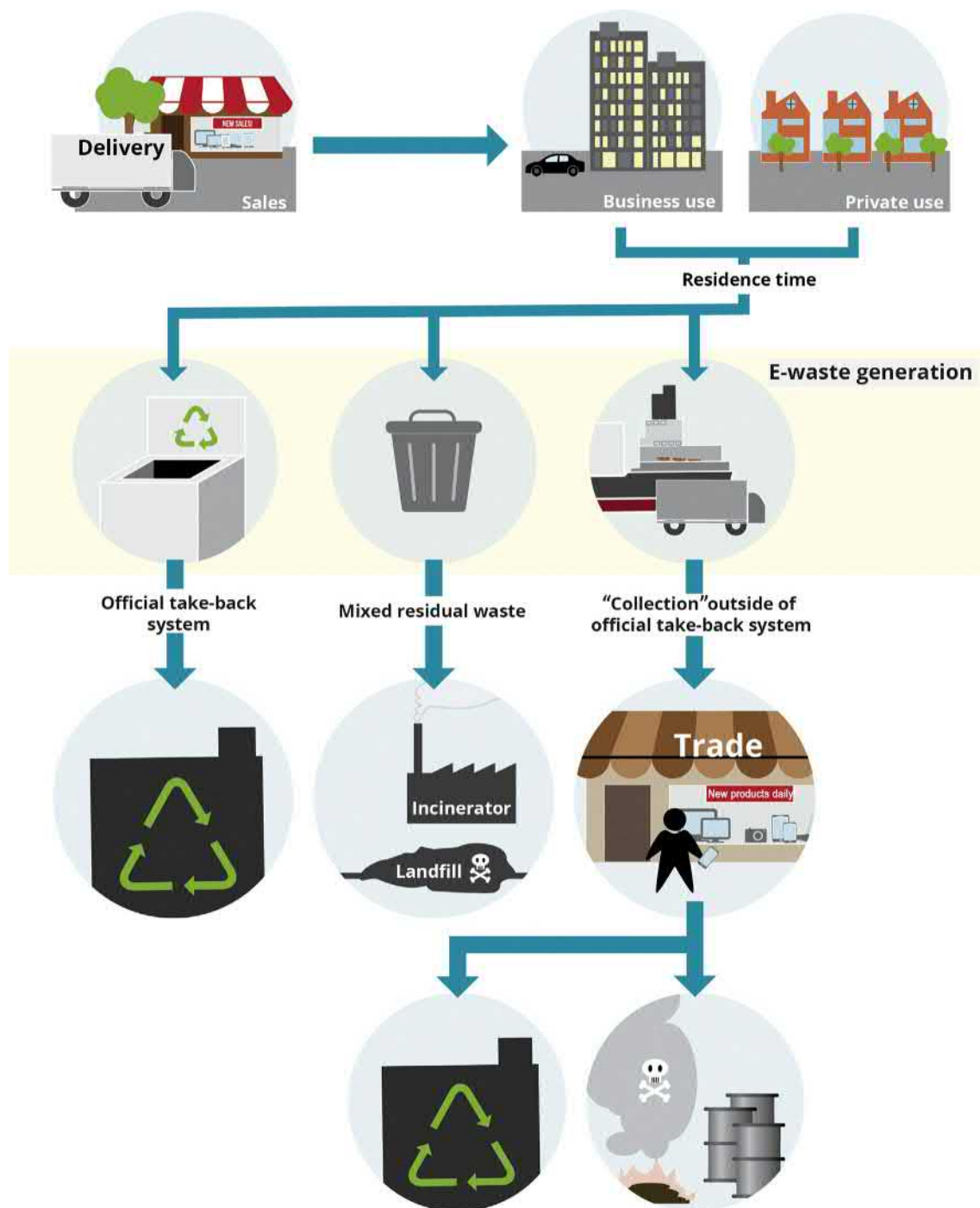


FIG. 25.3 Life cycle of EEE into E-waste, and the most common E-waste management scenarios [3].

E-waste under this scenario is usually not reported as part of the data described in the official take-back system scenario. Moreover, the collected E-waste is often also not treated in state-of-art facilities, and there is a potential for E-waste that is categorized as reusable is shipped off to economies in transition or to developing countries. These exports for reuse have been estimated in only a few countries. The CWIT Project estimates that between 5% and 15% of the E-waste collected in Belgium, the Netherlands, Great Britain, and Germany is exported and that in Belgium, the Netherlands, Great Britain, France, and Italy, between 10% and 35% of the total E-waste generated is recycled outside official take-back programs [5].

4.4 Informal Initiative

In most economies in transition and in most developing countries, the E-waste industry is dominated by self-employed people engaged in the collection and recycling. These are often unskilled workers paying for their living by collecting E-waste from consumers through door-to-door collection and selling on to refurbishers and recyclers. Collected products that do not have any reuse value are usually “backyard recycled” by informal initiatives through illegal means such as open burning, primitive acid baths, or direct dumping. All of these can cause severe damage to the environment and also to human health.

5 TOXIC SUBSTANCES AND URBAN MINING

The production of EEE is very resource intensive and as a result E-waste contains materials which may be hazardous, valuable, or indeed scarce. Common hazardous materials include heavy metals such as mercury, lead, chromium, cadmium, and chemicals such as ozone-depleting

substances which include chlorofluorocarbon (CFC), phosphors, hexavalent chromium, polychlorinated biphenyl, and various flame retardants. If the E-waste is not properly treated these elements and chemicals can potentially lead to health problems such as impaired mental development, lung damage through carcinogen inhalation, liver damage, and kidney damage.

In addition to these hazardous materials, E-waste may also contain valuable materials such as iron, copper, aluminum, and plastics and precious metals such as gold, silver, platinum, and palladium, all of which can be recycled. From a resource perspective E-waste can be considered as an urban mine providing secondary resources for remanufacture, refurbishment, and recycling. Overall UNU estimates that the worldwide resource of secondary raw materials from E-waste is worth $\text{€ } 55 \times 10^9$ (€ 55 billion) (see Table 25.1) [3] (see Fig. 25.4).

However, in order to exploit the opportunities and simultaneously mitigate pollution, good policies are needed that facilitate the creation of an infrastructure, ensuring that all collected E-waste is treated using state-of-art technologies and that green employment opportunities are created.

TABLE 25.1 Potential Value of Raw Materials in E-Waste in 2016 [3]

Material	Mass (kt)	Cost (10^6 €)
Fe	16,283	3582
Cu	2164	9524
Al	2472	3585
Ag	1.6	884
Au	0.5	18,840
Pd	0.2	3369
Plastics	12,230	15,043

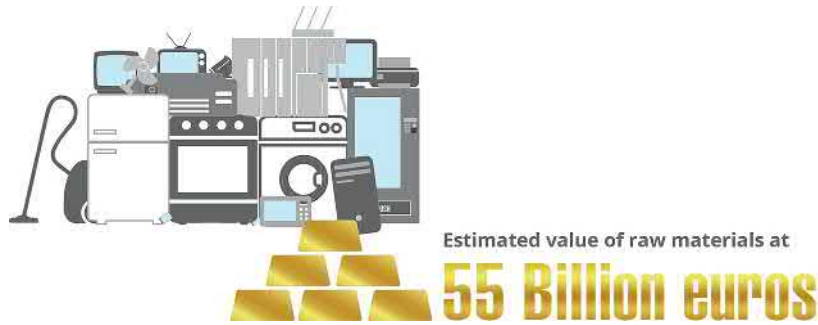


FIG. 25.4 E-waste's urban mine.

6 POLICIES AND LEGISLATIONS

In 2017 only 67 countries around the world had official E-waste legislations in place; this is reflected in the low level of collection and recycling rates described before. Furthermore, the limited amount of urban mining taking place has resulted in substantial losses of scarce and valuable material. In the EU the collection of the total generated E-waste since 2009 has remained at around 37% despite the EU aim that the member states should, by 2016, each have collected 45% of all E-waste and that this figure should reach 65% by 2019. This is an indication that sufficient enforcement is not taking place in the European Union as a prominent example.

On a transnational level, E-waste is dealt with by Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal which entered into force in 1992. The Basel Convention does not address E-waste as such, but it classifies hazardous waste in terms of the substances in the waste material. That is the Convention does not list, for instance, computers as hazardous and keyboards as nonhazardous. Instead, it classifies waste as hazardous or nonhazardous depending on the chemical properties of the waste. The Convention lists a threshold limit for each hazardous substance it identifies [6]. However, the major unsolved issue in the Basel Convention discussions is the distinction between waste

and nonwaste, because nonwaste is simply not covered. Therefore most shipments of equipment for reuse are unrestricted unless the exporting or importing country explicitly bans shipments of the used products. And for the enforcement authorities in customs or at ports it is hard to distinguish between used and brand new equipment because there are no trade codes specifying the distinction. Very often there are only a handful of officials manning customs posts at centers such as Hamburg, Rotterdam, or Antwerp and they have to make a decision when confronted with large numbers of containers of EEE. As a result, they simply follow their instinct as to whether the loads contain E-waste or not.

7 TRANSBOUNDARY SHIPMENTS

Linked to the challenge of dealing with the E-waste in the developed world is the primitive recycling practice sometimes referred to as the graveyard of the global North's luxury gadgets seen in some developing countries. The practice is reinforced by the associated photos and films of people, including teenagers, harvesting valuables from broken computers and TV sets, often surrounded by black smoke from the burning of the plastic parts of the machines.

However, there is no dispute among experts that E-waste from the more affluent parts of

the world such as the EU, the United States, Japan, and China is being exported to some African, Latin American, Eastern European, and Asian countries. The gateway for these exports is a classification of products as reusable. But in practice it is still very hard to determine whether something is reusable or not. This is not only related to the technical status of the product but also to the market of the importing country. As an example, the market for cathode ray tube V monitors is virtually over though many sets might be still fully functional for many years to come. For this reason, it may be very difficult for customs and port authorities to assess whether the exports and the imports are indeed E-waste or not. Certificates proving the functionality of machines declared for reuse are impossible to check because of the quantities involved; for example, one metric tonne of EEE may contain about 10,000 mobile phones. Appropriate packaging not only results in additional waste but might also not be the appropriate indicator especially with fully packed containers where the high-quality functional machines are in direct view of possible customs officials and E-waste products are hidden from view. In these cases, the only way to find out about the quality of equipment in the back part of a container is to completely unpack the container. Consequently, only spot tests are possible and scrupulous exporters are taking a chance that the major part of the container will remain undiscovered.

Some argue that a complete ban on the shipment of equipment for reuse might be the ultimate solution but this is certainly not taking the necessary life cycle perspective into account. The production of EEE is very resource intensive resulting in an enormous ecological burden. This can only be offset by an appropriate lifetime of use. Hence, the quicker a new product is wasted the higher will be the ecological burden. Taking this into account, the reuse of equipment, wherever it takes place, should be favored over immediate recycling. Furthermore, used

equipment is of great help in growing middle-class economies in transition and in developing countries, as it allows people to enjoy the benefits of the latest technologies. The solution is not only to provide the people with useable equipment but to develop schemes by which E-waste can also be appropriately recycled in these countries. It should be borne in mind that these countries do not presently have the necessary infrastructure for coping with E-waste.

8 BEST OF 2 WORLDS

The so-called Best-of-2-Worlds (Bo2W) philosophy has been developed within the multi-stakeholder StEP initiative. It provides for a network and pragmatic solution for E-waste treatment in emerging economies by seeking technical and logistic integration of “best” pre-processing technology in developing countries to manually dismantle E-waste and “best” end-processing equipment to treat hazardous and complex fractions in plants which are of a standard compatible with international state-of-the-art end-processing facilities [7].

As part of this work a series of dismantling trials was conducted on waste desktop computers, IT equipment, large and small household appliances in order to compare the environmental and economic performances of the Bo2W philosophy with other conventional recycling scenarios. The assessment showed that the performance of the Bo2W scenario is more eco-efficient than mechanical separation scenarios and other local treatment solutions. For equipment containing substantial hazardous substances, it demands the assistance from domestic legislation for mandatory removal and safe handling of such fractions together with proper financing, to cover the costs. Experience from Bo2W pilot projects in China and India highlighted key societal factors influencing successful implementation. These include market size informal competitors’ availability

of national E-waste legislation formal take-back systems financing and trust between industrial players. It was concluded that the Bo2W philosophy can serve as a pragmatic and environmentally responsible transition before the establishment of end-processing facilities in economies in transition and developing countries is made feasible.

9 DEMATERIALIZATION

Unfortunately, the present systems and schemes to sustainably get the E-waste challenge under control are failing. A key indicator for this is the low collection and appropriate treatment of E-waste. Furthermore, the introduction of electrical components into many new areas such as clothing and toys will contribute to add to the ever increasing E-waste mountain. This accumulation is happening in all parts of the world despite a growing saturation in the northern hemisphere for many product categories.

In the long term only models which take full control over the equipment in production usage and disposal can be successful. Nowadays, this is referred to as the circular economy model and has the backing of the European Commission. This type of approach has been around since the 1990s with projects names such as Zero Emissions/Waste Industrial Ecology Cradle to Cradle and The Natural Step—all with the aim of discussing strategic approaches to sustainability with the aim that all wastes and emissions should again become resources. This urban mining will result in a substantial decrease in the mining of virgin material from the earth's crust.

In the short term the collection of E-waste must substantially increase followed by appropriate treatment in state-of-art facilities. For this to happen, models must be explored the way to ease the return of equipment no longer in use and possibly reward the consumer. This could be done, for example, through a public collection of containers for E-waste; or through a mixed

collection of paper and E-waste which could be easily separated upon take-back; together with financial benefits to the people returning machines and purchasing a new ones. Deposit systems are not especially favored by industry because it is binding for too long a time, which ties up financial resources and results in time consuming and costly administration.

However, a possible way out might be a complete rethinking of the way we buy and use EEE. Presently the ownership of the equipment goes from the manufacturer/service provider to the consumer purchasing the equipment. But what would happen if the consumer only purchases the service from the equipment provider? Then the ownership of the equipment remains with the manufacturer/service provider putting them in the position to take full responsibility for their products over the entire life cycle. As a consequence, the manufacturer/service provider would collect the machine equipment when they no longer provide the necessary services the consumer subscribed to. The manufacturer would then redesign the equipment to make maximum economic reuse of equipment components and materials. In this way both the manufacturer and service provider would gain from the full life cycle of each piece of equipment. Such an approach would be moving away from a system focusing on the equipment *per se* and would instead focus on dematerialization and the full life cycle of each piece of equipment. Substantial leakage from the present supply and collection chain through, for example, incinerations mixing with other waste streams during international shipments or even long-time hoarding in cellars cabinets and attics could be avoided.

Nevertheless and despite the facts that E-waste is the fastest growing solid waste stream, some manufacturers argue that the E-waste issue is no longer high on their agenda. This attempt must be regarded as an important political maneuver moving away from the association of E-waste with illegal and environmentally unsound practices.

These companies argue that they are now addressing E-waste under their circular economy approaches, though their approaches are still reflecting a linear, non-life-cycle thinking. Hence, one can call it window dressing and it will not diminish the reality that E-waste will remain a major waste issue in the coming years unless it is dealt with by the highest level of attention.

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Tire Recycling

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1 INTRODUCTION

Tires are an essential part of the economy of every country that relies upon vehicular and/or air transport to move people and goods. Although the overall rubber sector is small in comparison to others, tires are a significant part of international and domestic trade. Frequently imported for use, they are often retreaded, recycled, or recovered locally.

Table 26.1 presents the relative annual consumption of key material and product streams in the European Union (EU). While the total quantity of rubber used is relatively small, the product units are comparatively large, and the resulting wastes are conspicuous and unattractive.

The combined annual global production of natural and synthetic rubber has grown to approximately 33×10^6 t (33,000 000t), of which about 75% is consumed by various divisions of the automotive industries. The preponderance, about 60%, is used for the manufacture of tires for passenger cars, utility vehicles, and commercial trucks. Smaller diverse categories are grouped as 'other,' which include tires for off-road vehicles, such as agricultural, civil engineering, industrial, mining, airplane, among others as well as bicycles and motorcycles. Hundreds of nontire automotive products including appearance items, belts, hoses, housings, moldings, rings, seals, among others, utilize the remaining 15%.

TABLE 26.1 Examples of EU Waste Streams

Product	Approximate Mass (t) Use	Subset
Paper	79,000,000	
Plastics	37,000,000	
Packaging		19,980,000
Glass	15,000,000	
Aluminum	8,860,000	
Rubber	5,000,000	
Tires		3,200,000

Table 26.2 presents the dramatic increase during the past 10 years, particularly in Asia, Oceania, and the Middle-East. During the past decade global tire production effectively doubled to $>1.8 \times 10^9$ units in order to maintain pace with the burgeoning vehicle parc primarily in nontraditional markets [1].

In general, passenger car tires account for slightly $>90\%$ of production, while truck and “other” categories constitute the remaining 10% [2]. Annual sales are divided into two principal categories: original equipment, that is, those that are purchased or delivered with the vehicle, and replacement tires, that is, those that are fitted after use to replace the original. The

TABLE 26.2 Motorization Increase 2005–15

Region	% Increase
NAFTA countries	6
Other American countries	60
EFTA Countries	9
Other European countries	59
Africa	35
Asia, Oceania, Md East	141

Data from Organisation Internationale des Constructeurs d'Automobiles, OICA 2017, OICA, Motorization Rates, 2015. www.oica.net/world-vehicles-in-use-all-vehicles-2/.

general rule for annual waste prediction is that for each tire sold, rather than those manufactured (whether newly manufactured, part-worn, or retreaded), one tire will become waste.

Almost simultaneously, as tire production doubled, indications are that natural rubber production has begun to decline, primarily in Malaysia and India [3, 4] posing a potential threat to the continued exuberant growth of supplies for the automotive industries. As a result, larger quantities of synthetic rubbers are being used and tire manufacturers are beginning to look toward high quality recycled materials to fill the emerging gap. The infrastructure that will enable a continuous flow of recycled tire materials (RTMs) that can be used in substitution of dwindling virgin resources is in place within the European Union, North America, parts of Asia, and other regions of the world.

In 2016 about 3.2×10^6 t, (3,200,000 t) of tires were classified as waste in the EU, with comparable quantities arising in North America and also in Asia. However, it should be noted that in many countries within and outside of the EU, the category of ‘other’ is often not included in the annual waste count. As an example, in the EU, the inclusion of off-road tires (OTRs) would add another approximately 350,000 t to the total.

Fig. 26.1 illustrates the five phase life cycle of the tire from production through disposal. In understanding Fig. 26.1, it is important to note that:

1. *Production*: tires produced in the EU must meet rigorous environmental, material, and performance standards prior to on-road use, accommodating the ban on certain extender oils (2010);
2. *New tires*: tires placed on European markets are required to meet stringent EU, national and industry standards for road and/or special purpose use and exhibit a fuel economy label;
3. *Part-worn roadworthy tires*: meet EU, national and international standards for continued on-road use domestically and for export;

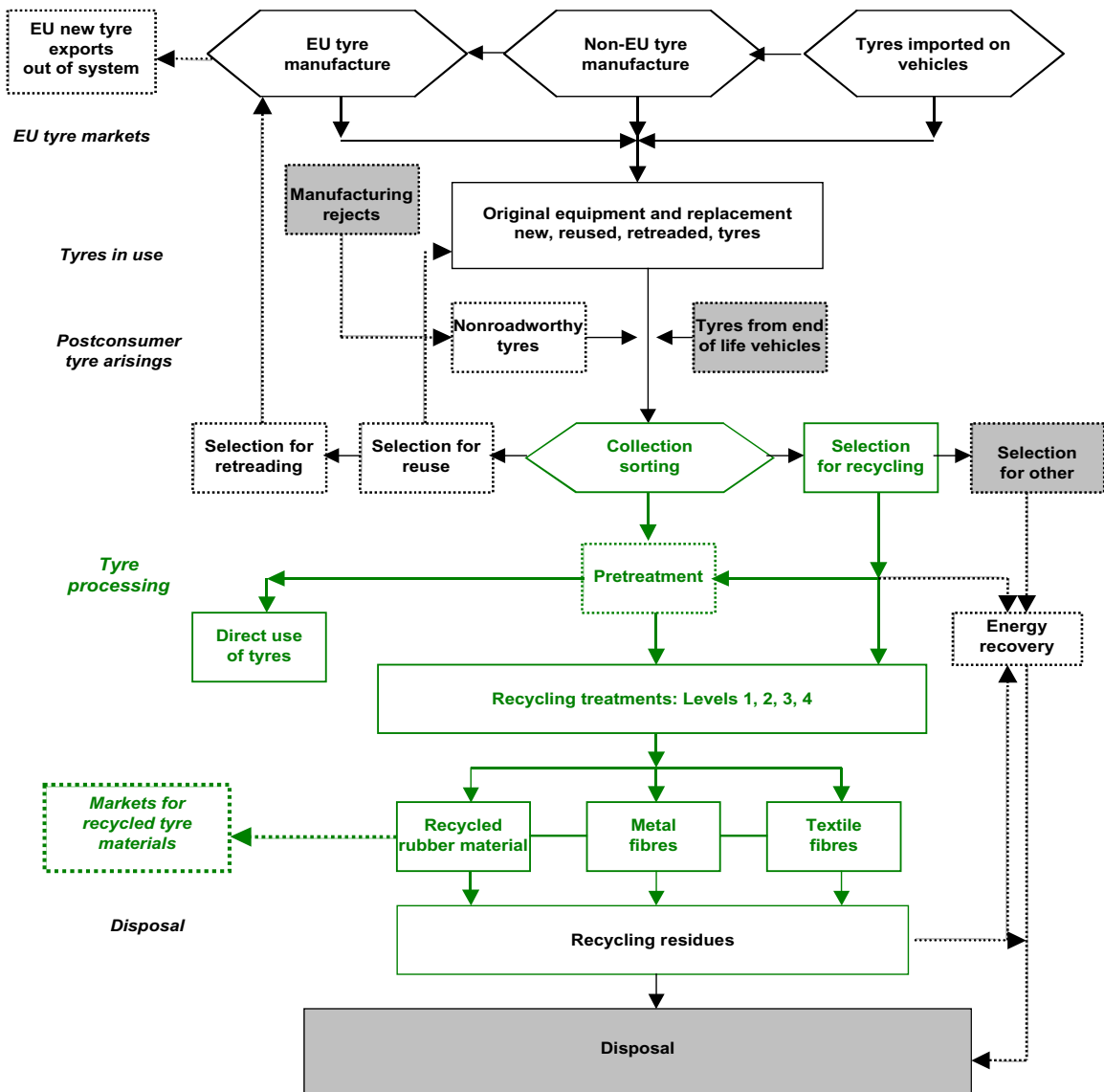


FIG. 26.1 The tire life cycle.

4. *Retreadable casings suitable for retreading:* an interim step for continued on-road use, as defined by the retreading industry;
5. *Recyclable tires:* nonreuseable or retreadable tires that have not been involved in a fire are free of oil, fuels, and other contaminants.

2 THE TIRE: THE RAW MATERIAL FOR RECYCLING

A pneumatic tire is often described as an engineering marvel. It is basically a large, round, hollow shell filled with compressed air that can

TABLE 26.3 Composition by Mass of EU Car and Truck Tires

Material	Car/Utility (%)	Truck/Bus (%)
Rubber/elastomers ^a	48	45
Carbon black/silica	22	22
Metals	15	25
Textiles	+5	–
Zinc oxide	1	2
Sulfur	1	1
Additives	8	5

^a Natural/synthetic rubber ratio “truck tires ± 1 –2 car tires ± 3 –4.

support more than 50 times its own weight. While the external features have not changed perceptibly since radial tires were introduced more than 70 years ago, numerous internal changes have improved their durability, performance and environmental sustainability. Many ingredients that improve longevity, resistance

to abrasion, and so on, during on-road life, also contribute to the effectiveness of recycled tire materials in products and applications downstream. The composition for the tires of EU vehicles is summarized in [Table 26.3](#).

[Table 26.3](#) details the composition by mass of car and truck tires in the EU Market; the data reflects the generic formula for tires produced for this market. Material composition varies by category, that is, car or truck, and so on, and nominally from continent to continent (Asia, Europe, the Americas, Africa) although the ingredient ratios remain relatively the same. The variations have negligible impact on use, driveability, wearability, or recyclability.

No matter where the tire is produced, all tires contain four fundamental material groups: natural and or synthetic rubbers, carbon blacks/silicas, reinforcing material (metals/textiles), and facilitators. The four material categories used in tires is given in [Table 26.4](#).

The compounding process modifies the hardness, strength, and toughness of the rubber and

TABLE 26.4 The Four Material Categories

1. Natural and synthetic rubbers (%)	40–48	Ratio of natural to synthetic rubber: 2–1 truck tires; 4–3 car tires Different polymers and additives are used in each part of the tire
2. Carbon blacks and/or silica (%)	22–27	A range of carbon blacks of varying sizes, structures, and characteristics is used in different parts of a tire. Larger sizes are used in the inner liner, smaller particles are in the casing and tread
3. Reinforcing materials (%)	5–25	
Metals (%)	15–25	In the beads, belts, and casings of a truck tire
	11–13	In casings and plies of a car tire
Textiles (%)	5–10	Textiles are used in car tire casings. Natural rayon and nylon in the EU, polyesters in the United States and Asia are used for casing cords
4. Facilitators (%)	8–0	Extender oils, waxes, plasticizers aid processing, improve performance, or facilitate curing; Curing systems can include sulfur, zinc oxide, stearic acid, peroxide, and accelerating agents; Antioxidants, antiozonants, and so on, protect the compound; several varieties of carbon blacks/silicas increase mechanical properties and are evenly distributed throughout the matrix; clay, whittings, and so on, are fillers.

increases its resistance to abrasion, oil, oxygen, chemical solvents, and heat. While each manufacturer has its own formula to provide unique characteristics, tire compounds in general share many similarities and contain all of the ingredients necessary for quality on-road service and durability.

Once the ingredients are compounded and the tire structure assembled, the unit is vulcanized. Vulcanization is a thermochemical process that cures the rubber by incorporating sulfur and/or other accelerators, for example, peroxide, zinc oxide, stearic acid, and so on, into the rubber compound. The accelerators form cross-links between the sulfur and the carbon in the rubber, producing a chemical bond that improves the physical and mechanical properties of the rubber.

Vulcanized rubber is transformed into a strong, elastic, rubbery hard state, which is less gummy, stronger and resistant to heat, frost, and many corrosive materials. The final tire structure is an integrated whole, ready to be mounted on a vehicle and roll on the road until it reaches the end of its on-road life. However, prior to on-road use, each tire must meet a broad range of rigorous industry-based and national tests and standards.

A tire can reach the end of its on-road life at almost any point after production and on-road initiation. Once a tire has been permanently removed from a vehicle without the possibility of being returned to the road, it is defined as 'waste.' From that point forward it enters into a waste management system. Tires within and outside of the EU are considered a "priority waste stream" and must be handled according to international and national waste management legislation.

3 MANAGEMENT OF POSTCONSUMER TIRES

Tire management is greatly influenced by environmental legislation at International, EU, State, and often Regional or local levels. Each has had

an important impact on the overall system from designs for collection—to recycling—and recyclers—from organizing and sourcing raw materials, to financial support for product design, development, commercialization and marketing, and the final disposal of recycling residues.

Three directives were enacted almost simultaneously in the EU to ensure that the greatest volume of tires would be diverted from landfills and treated in a sound and sustainable manner. The Landfill Directive (1999) [5] banned the landfilling of whole passenger car and truck tires as from 2003 and tire by-products from 2006. Tires identified as 'other' were excluded from the ban. The overall aim was to divert the majority of tires away from landfilling or similar 'internments' and toward more sustainable means via material recycling or energy recovery facilities.

The End-of-Life Vehicle directive (2000) [6] required the removal of tires from vehicles prior to demolition to ensure that tire remnants would not end-up in landfills. Finally, the Incineration of Waste directive (2000) [7] aimed at reducing dioxin emissions 90% by 2005 resulted in controls on the use of tires for energy recovery and inadvertently diverted tires toward material recycling. Cement kilns were later brought into line with other incineration facilities.

The revised Framework Directive on Waste (2008) [8] has likewise had a critical impact by directing waste tires toward recycling and away from landfilling. Further, it provides a definition of "recycling" and offers the means for recycled materials to exit the waste designation:

Recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

Five waste streams were identified as "specified wastes (to) cease to be a waste." Each requires "specific criteria" to be defined and

prepared to end their “waste status”: *aggregates, paper, glass, metal, tires, and textiles*. Thus, although tires are not currently the subject of specific legislation, they are identified as among those materials and products that require ongoing consideration.

Table 26.5 briefly describes the “four Rs” of sustainable waste-tire management, which through their use, minimizes waste and reduces reliance upon natural resources by recycling and/or recovering their material and economic value. The four are reflected in the EU five-step waste management hierarchy which places material recycling at the top of the list.

Tire recycling is unique in comparison to other recycling sectors for a variety of reasons:

- First, tires are among the smallest waste streams, however when recycled, they result in not one but three material streams: rubber, metal, and textile fibers—each of which is currently commercialized;
- Second, tires are essentially homogeneous, that is, all tires are produced from the same materials, using virtually the same generic formulae with nominal variations—worldwide. The principal variation is size;
- Third, there is an interim treatment before a tire is defined as waste—retreading, which can extend the on-road life of a tire;
- Fourth, recycled tire materials (RTMs) are not used to produce the same products as the original but have become strategic materials in over 50 different market sectors from shoes to roads, hoses to sport surfaces, window seals to vibration mats for trains and trams—among hundreds of other products and applications;
- Finally, under EU legislation tires, tire pieces and recycling residues cannot be placed in landfills, compelling the development of new options for valorization that will take their place in the circular economy.

The starting point for tire recycling is the same as for other industries—the sourcing of a continuous flow of raw materials. Historically, tires have been separately collected and sorted for two sectors—the part-worn market (second-hand) and retreading. However, as retreading dwindled, material recycling and energy recovery operations began to absorb a majority of the tires. In many countries with large retreading industries, the infrastructure for collecting, sorting, and transporting tires became the means of servicing these new markets, that is, recycling and energy recovery.

Today, in most EU States, North and South America, many parts of Asia and elsewhere, tires destined for recycling are collected under commercial contract from a variety of sources including garages, retail outlets, and vehicle dismantlers, among others. In some regions they are also removed from long-standing stockpiles or “mono-fills.”

Generally, prior to delivery to a treatment facility the tires are sorted by category, that is, car, truck, other, and then by size. Roadworthy part-worn tires are removed for domestic reuse or export under OECD regulations. Retreadable casings are diverted to appropriate facilities according to industry criteria. Nonretreadable tires are delivered to a treatment site. As postconsumer tires are a waste, they must be shipped in compliance with the Basel Convention and

TABLE 26.5 Sustainable Options

Reuse: Includes the sale of part-worn tires for continued on-road and other uses as well as for export to countries with less restrictive road-use requirements

Retreading: Remanufactures a carefully selected, un-damaged casing as its core to reduce production energy as well as virgin resources

Recycling: Transforms a waste into a raw material that will be reintegrated into the economic stream as a resource in substitution of virgin resources

Recovery: Transforms a waste into energy or fuel, to be reintegrated into the economic stream as a resource in substitution of other virgin energy options

OECD regulations. As they are nonhazardous waste destined for recovery, the documentation and information required may be minimal, although that may change under new Basel discussions beginning in 2018.

Once delivered to a treatment facility the tires come under the jurisdiction of national, regional, or local authority(ies) which regulate the quantity, location, circumstances, and duration under which they may be stored on the premises. Appropriate zoning and land-use permission, permits, and licenses must be obtained. Under certain circumstances, a waste management permit may also be required before the tires can be processed or the materials used.

Prior to processing, the tires are sorted; cleaned of debris such as glass, stones, and so on; and stored for use. Tires removed from stockpiles or other long-term storage (mines, wharfs, etc.), often must be washed prior to use.

4 MATERIAL RECYCLING: TREATMENTS AND TECHNOLOGIES

Tire recycling treatments range from the simplest mechanical cutting or compression devices to sophisticated, complex multiphase chemical, mechano-chemical, and/or thermal processes, which overcome many of the principal obstacles inherent in the recycling of thermoset rubbers. Specifically, the treatments and technologies that have evolved do not attempt to dissolve or melt the rubber into the virgin compound. Rather, they aim to exploit and enhance selected properties of the compound. It must be noted that the following discussions refer only to recycled tire materials that will reenter the economic flow for use as ingredients or materials in compounds, applications, or products. They do not include materials that are prepared for use for energy, cement kilns, or other similar purposes although in some instances the treatments do overlap.

There are four basic levels of treatment. Each can be described in terms of its basic functions, which become increasingly complex as they progress through successive levels. Capabilities can be expanded by repeating a process or by linking two or more technologies to operate in tandem in order to produce the desired result.

Levels 1 and 2 treatments currently produce approximately 70% of all recycled tire materials used today, down from 81% in 2010, and, thus, will be a major focus of this discussion. It must be noted that until recently the sole output of Levels 1 and 2 was rubber. However, during the past decade, treatments have succeeded in obtaining metals and textiles as well—accounting for $\pm 1\%$ of all outputs.

Further, during 2016–17, Level 3 and 4 treatments have gained considerable momentum and have begun to be identified in performance results. During this period, third and fourth level treatments accounted for 8% of RTM outputs as “specialty powders.”

Fig. 26.2 presents a schematic diagram of the four levels of treatment and illustrates the progressive, often inclusive nature from the “first cut,” by mechanical means, through the “higher level” specialized treatments and technologies which add distinctive characteristics or properties to the material outputs.

LEVEL 1 TREATMENTS: DESTRUCTION OF THE STRUCTURE OF THE TIRE

These treatments use car and truck tires as feedstock. They are simple mechanical means which destroy one or more of the physical attributes of the tire, that is, shape, weight bearing capacity, rigidity, among others. They are designed to produce materials that can be directly used for simple products in civil or environmental engineering or as feedstock for further recycling. The most common methods include bead, sidewall or tread removal; compression; baling; or cutting.

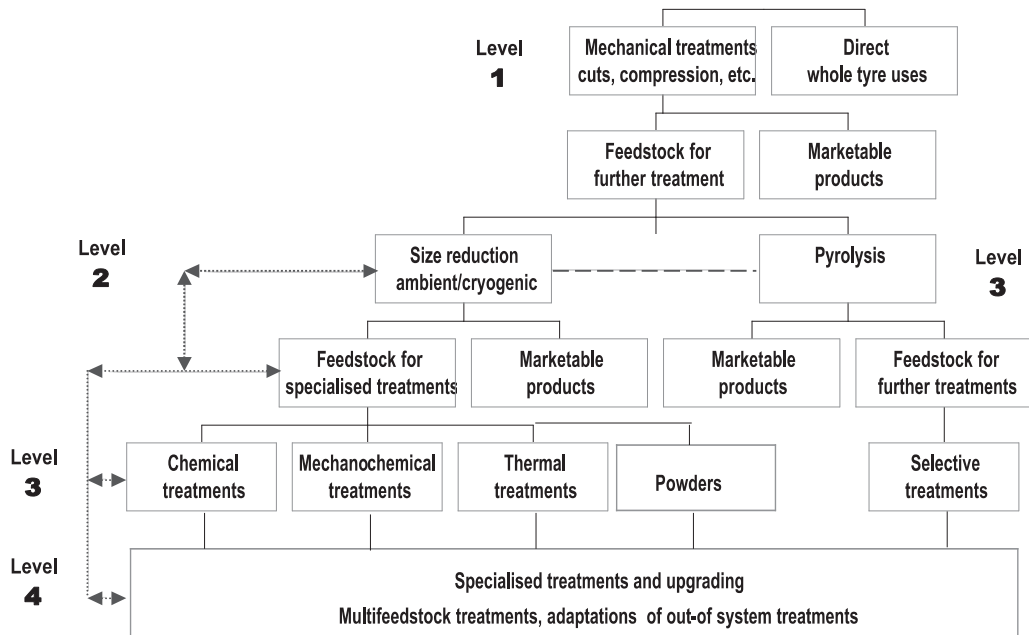


FIG. 26.2 Schematic of the four levels of treatment.

Bead removal is used for car and truck tires as a pretreatment for later recycling. It is a mechanical procedure that removes the rubber-coated steel coil wires by cutting or tearing the points that anchor the bead to the casing. The carcass can be directly used for civil engineering applications or as feedstock for later recycling.

Sidewall removal is used primarily on car tires as a pretreatment for later recycling treatments or the sidewall can be used directly in civil engineering applications. It is a mechanical cutting procedure that frees the strips of tread from the carcass. The tread can be used directly in simple products or as feedstock for later processing.

Baling is used on car and truck tires. It is a mechanical procedure that destroys the structure of a specified number of tires by placing them in a chamber under high pressure (approximately 65t) to permanently deform them into a cube or rectangular solid which is then secured with a defined number of straps at specified points.

The number of tires is dependent upon the final dimensions of the bale. They can be used directly for a number of civil engineering uses.

Equipment can be stationary or mobile dependent upon how or where the material will ultimately be used. Thus, a baler could be placed on-site during an erosion control project. Other than in debanding, neither the bead wires nor the belts are removed prior to or during processing.

LEVEL 2 TREATMENTS: LIBERATION AND SEPARATION OF THE ELEMENTS OF THE TIRE

These treatments separate out the principal components of the material, that is, the rubber, metals, and textiles. The most common technologies are ambient and cryogenic size reduction as well as some newer technologies such as microbes, water jetting, among others, to treat the tires.

Whole tires and Level 1 outputs are generally used as feedstock. The outputs can be used directly in applications or products or as feedstock for Level 3 processing.

Shredding and chipping are used on whole car or truck tires. Shredding is a treatment that uses different technologies to fragment the tire. Most often, a set of knives is used to produce material of approximately 50–300 mm that is irregularly shaped or equidimensional. Neither the bead wires nor the belts are removed prior to, during, or after processing unless it is accomplished as the first step in size reduction processing.

Chipping is generally a second processing of shredding which results in material of approximately 10–50 mm that is either irregularly shaped or equidimensional. Chips are often used directly in civil engineering applications, for tracks or fill, and often as feedstock for ongoing Level 2 treatments.

Ambient grinding uses whole or pretreated car or truck tires in the form of shred, chips, side-walls, or treads. Ambient grinding is a multistep technology. Processing takes place at or above normal room temperature. The rubbers, metals, and textiles are sequentially separated out. First, the material is sheared with a system of knives. If the reinforcing and bead wires are not removed prior to processing, the metals are magnetically separated out during the granulation process. The material may continue through one or more sequential granulators to further reduce it in size. The material passes through a series of screens and sifting stations to remove the final vestiges of impurities and ensure consistency of size. During the final phase, the textile residues are removed by air separators.

Cryogenic processing generally uses pretreated car or truck tires as feedstock, most often in the form of chips or ambiently produced granulate. Processing takes place at very low temperature using liquid nitrogen or commercial refrigerants to embrittle the rubber. It can be a four-phased system which includes initial size reduction, cooling, separation, and milling. The material

enters a freezing chamber where liquid nitrogen is used to cool it below the point where rubber ceases to behave as a flexible material. The cooling process embrittles the rubber and allows it to be fractured to the desired size resulting in a smooth and regular shape. Because of its brittle state, fibers and metal are easily separated out in a hammer mill. The granulate then passes through a series of magnetic screens and sifting stations to remove the last vestiges of impurities.

Both ambient and cryogenic processing can be repeated to produce finer particles. Increasingly, with their attendant technologies, the two are combined into one continuous system to benefit from the characteristics and advantages of each and to reduce overall costs. An ambient system is generally used in the initial size reduction phases. The cryogenic system is used to further reduce the material in size and then to remove the metal and textiles. The outputs from either or both systems can be used directly or as feedstock for further processing.

Within the past decade, these size reduction technologies have begun to produce sufficiently clean steel and textiles that can be used as input materials for later treatments with commercially viable results. Thus, the recycling residues have begun to enter the economic flow as additional material streams.

LEVEL 3 TREATMENTS: MULTITREATMENT TECHNOLOGIES

This group of diverse treatments and technologies further processes the first and second level material outputs to modify one or more characteristics by means of mechanical, thermal, chemical, mechano-chemical, or multitreatment procedures. The outputs of Level 2 are most often used as feedstock.

Reclaim, pyrolysis, surface modification, and devulcanization are representative examples of the range of treatments used. The outputs can

be used directly in applications or products or as feedstock for Level 4 processing.

Reclaim is a two-phased process during which the material is thermally broken down. Part 1 relies upon clean, ambiently produced granulate. The second part is plasticizing during which the granulate is mixed with the chemical agents and oils, subjected to heat, then worked mechanically, extruded, and cut into blocks. Key elements that influence the output are the chemical composition of the material used, the duration of the breakdown process, and the ratio of thermal to mechanical breakdown. A principal characteristic of reclaim is that it can be modified during processing and customized for specific uses. The vast majority of reclaim is returned to the automotive industry for a range of products including tires.

Pyrolysis is a two-stage thermal decomposition which heats the rubber in the absence of oxygen to break it into its constituent parts, that is, carbon, oil, steel, and so on. The principal stages are primary cracking and postcracking. Depolymerization and primary cracking take place progressively by heating the material at relatively low temperatures while aromatic components are produced at higher temperatures, although both can occur in a one-step furnace. Pyrolysis produces a minimum of three commercializable products including saleable steel, oils, and carbon products. The resulting carbon products have proven viable as a replacement for some types of carbon black for use in inks, toners for photocopiers and printers, paint, and even tires.

Devulcanization is a process that can be undertaken by different means including microwaves, ultrasound, biologics, chemicals, among others. The goal is to reverse the sulfur-carbon cross-links that were formed during vulcanization so that the material can be reformatted and revulcanized. Different processes modify specific properties of the rubber. The system used will determine whether it will be a batch or continuous process. Each devulcanization system

begins with a first phase of either cryogenic or ambient size reduction. As an example, chemical processing utilizes a batch processing.

Surface modification/activation uses buffings or peelings from retreading or ambiently size reduced granulate produced from truck tire treads as principal feedstocks. Surface modification is a three-phase treatment. In the first phase, the feedstock is ambiently reduced to a fine powder of $>0.04\text{mm}$ from which all metals and textiles are removed. In the second phase the powder is activated by coating it with high molecular unsaturated polymers in aqueous dispersion with an appropriate curing system. The third phase occurs during vulcanization on a double belt press that rolls the material at very high pressure. During the curing process bonds are formed between the polymer chains of the coating and the polymer to which the powders are added. As a result the rubber particles activated by the coating are bound to a new three-dimensional network. The original rubber properties are retained.

LEVEL 4 TREATMENTS: MATERIAL UPGRADING

Level 4 treatments refine, upgrade, modify, or generate specific characteristics or properties in materials produced by Level 3 treatments, which most often provide the feedstock. Upgraded reclaim, reactivated, surface modified or devulcanized materials, upgraded char (carbon products) and new compounds are among the most representative outputs.

Posttreatments of pyrolytic char include mechanical separation, physical or chemical treatments that can upgrade the char by reducing it in size and separating out impurities. Posttreatments generate materials that have similar characteristics to a variety of different grades of carbon black currently used to produce a broad range of commercial products and are a valuable resource for technical rubber goods. Resonance

disintegration is an innovative example of particle fragmentation using resonance forces to vibrate particles apart. It can take pyrolytic char from a maximum of 600 μm to below 30 μm with 50% below 1 μm after a single processing with a surface area, structure, and dispersion in the rubber compound similar to standard carbon blacks.

Thermoplastic elastomers use granulate and/or powder produced from car or truck tires as feedstock. The treatment requires two feedstocks: rubber and plastic. It is a two-phased reactivation and mixing process which combines the material qualities of the former with the processing behaviors of the latter. The reactivation and mixing occur under high shear forces in a conventional internal mixer. The granulate acts as an elastomeric compound during the rubber phase in cross-linked thermoplastics creating a new compound—not a blend.

As a rule, smaller sized materials retain fewer impurities from metal or textile. As speciality treatments generally use smaller granulate or powders as feedstock, there is usually no further loss during processing. One of the few exceptions could be the upgrading of pyrolytic char and removal of extraneous ash, and so on. A summary of the four treatment levels is given in Fig. 26.3 and provides examples of some of the most notable outputs and applications from each of the technologies and treatments.

The material outputs from the four levels of treatment are broadly classified into six categories: cuts, shred, chips, granulate, powders, and fine powders. A majority of the fine powders result from the third and fourth levels.

The range of recycled tire materials is summarized in Fig. 26.4 and shows the continuum of materials that result from the various treatments. Each category is comprised of one or more subcategories with different parameters, creating a continuum from <500 to >300 mm.

The apparent overlap between the larger granulate and the smaller chips is a function of the processing specifications. The granulate is

characterized by a multistep processing in which the metals and textiles are removed, while the chips are characterized by a process which fragments the tire leaving the metals and textiles intact.

Evaluations and standardized testing procedures are used to ensure material consistency over time. The methods used vary according to the material size. Larger materials, that is, cut tires, shred, or chips are generally evaluated visually. For example, attention is paid to the size of the material in different directions and the presence of extraneous materials such as glass, free wires, stones, or other debris. Other criteria may be agreed between the producer and the user.

With smaller sized materials that is, granulate or powder, more exacting methods are used. As can be seen, each category and subcategory is characterized as a range. However, the fragments in each subcategory are not homogeneous, but constitute a range of different size particles. Thus, a sample of 1-mm powder contains particles ranging from <0.30 mm to >1 mm. The distribution in the sample should show that >90% of the particles are within the 0.30–1 mm range.

Particle distribution is determined with an established series of screens. Dependent upon the size of the material, a set number of screens is placed in descending order. The material flows through each tier within a specified time which is noted and used in the final calculation. The material that remains on the screen is weighed and expressed as a percentage of the sample. While the size and particle distribution are often critical to the selection of a material for a particular product or application, the chemical and physical properties provide information about the material content and how it will react physically in response to certain conditions.

Each material range from granulate to fine and speciality powders follows a specific set of performance protocols as defined by the sector for which the material will be used. Guidance

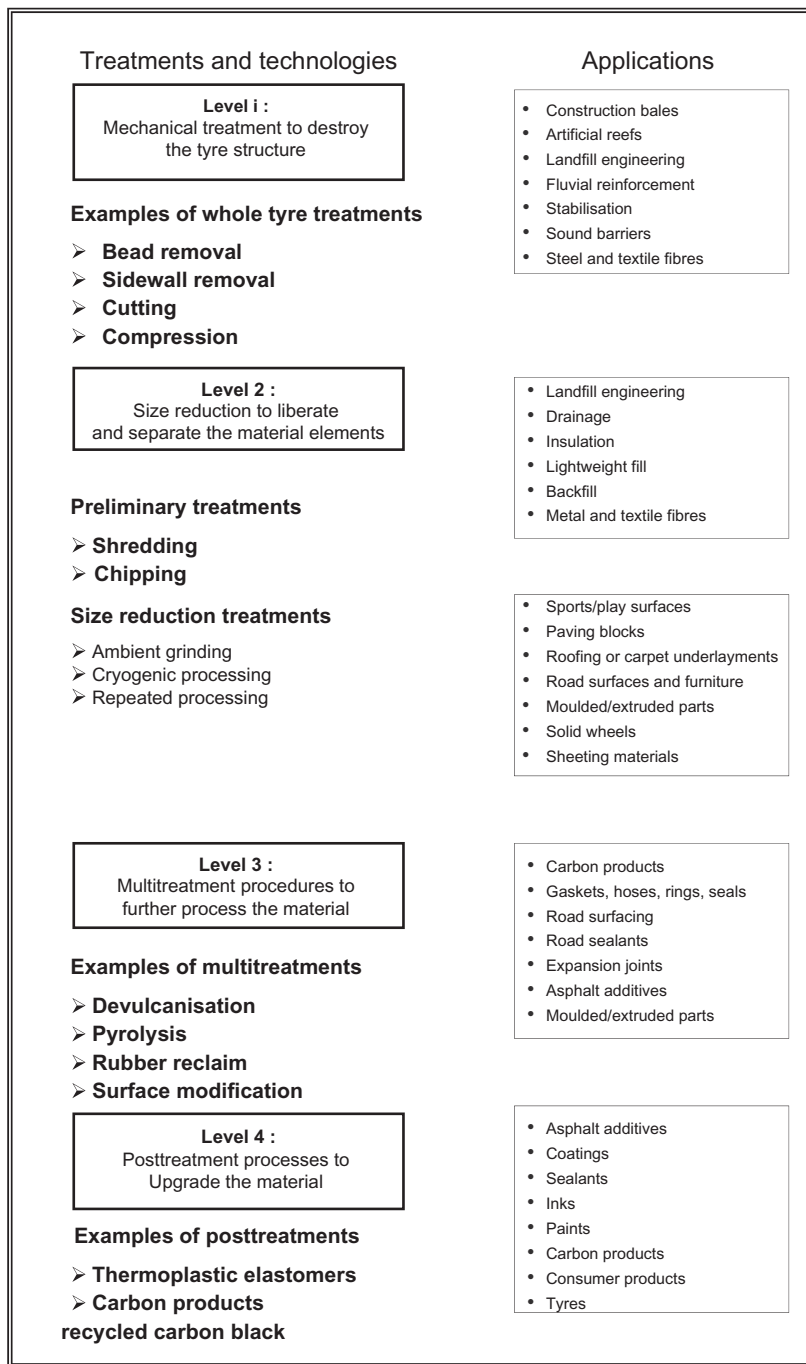


FIG. 26.3 A summary of the treatment levels.

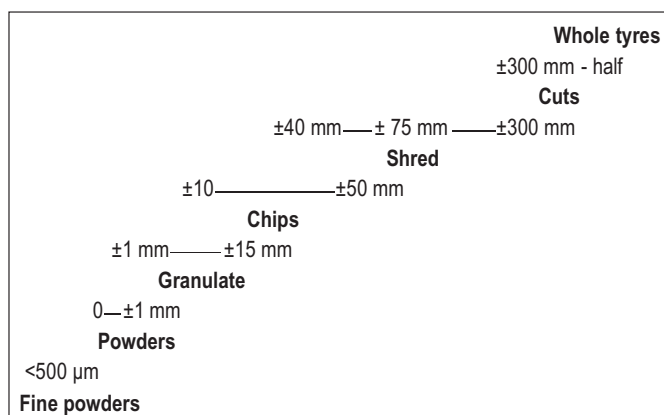


FIG. 26.4 The range of recycled tire materials resulting from the treatments.

standards are available for these materials from the European Standards Bureau (CEN), ASTM International, or ISO International Standards Organisation).

The principal material characteristics of the outputs are summarized in the four columns of [Table 26.6](#):

1. *Material*: the type of material and how it is processed.
2. *Size*: each material is described as a range of particle sizes, for example, granulate can be described as a range from ± 0.5 to ± 15 mm, while devulcanizates are described as less than 1 mm. Whole tires are discussed as a unit, and bales by the number of tires required to produce a unit.
3. *Key characteristics*: describe some of the principal characteristics of the particular material which can distinguish it from other materials of the same size, for example, granulate produced ambiently and cryogenically present very different characteristics.
4. *Traditional materials*: lists some of the traditional materials for which particular postconsumer tire materials could be used as substitute for virgin resources.

5 TRADITIONAL AND EVOLVING MARKETS

During the past 25 years tire recycling has made great strides toward meeting its goal of producing high performance, environmentally sustainable and commercially competitive materials. Produced from a priority waste stream, these materials contribute to the circular economy by substituting for virgin resources, reducing energy consumption for production as well as CO₂ emissions.

Significant quantities of material are produced annually with indications that capacity will continue to grow, based upon the expansion of the automotive market and inclusion of currently uncounted tire streams. Treatments and technologies have evolved to new levels of sophistication and efficiency which allow the production of finer, cleaner and more complex materials, at more competitive prices.

Six large traditional markets, coupled with a number of smaller niche markets, consistently consume >75% of the recycled tire materials produced annually. Newer niche markets, many of which have the capacity to use increasingly sophisticated materials, are beginning to evolve, albeit slowly. Until today production and use

TABLE 26.6 Summary of Material Characteristics

Material	Size	Key Characteristics	Traditional Materials
Whole tires	Unit	Lightweight, low compacted density, high void ratio, good Compressibility, water permeability, thermal insulation	Concrete block, clay, quarried Aggregate, gravel filled drums
Construction bale	100–125 tires	Lightweight, low compacted density, good thermal insulation, limited deflection, exceeds specifications for specific gravity, gravity, compressibility, deformation, creep, hydraulic conductivity	Construction block, stone riprap, gravel, packed earth, crushed rock in wire cages or other containers
Shred	$\pm 50\text{--}\pm 300\text{ mm}$	Lightweight, low compacted density $\pm 0.5\text{ t m}^{-3}$, high void ratio with good water permeability between 10^{-1} and $10^{-3}\text{ m}^{-\text{s}}$	Crushed rock or gravel, large rain sand, lightweight clay or light expanded clay aggregate, fly ash from coal burning
Chips	$\pm 10\text{--}50\text{ mm}$	Good thermal insulation and compressibility, low earth pressure and high friction road characteristics	
<i>Size reduced</i>		<i>Dependent upon use</i>	
Ambient	$\pm 0.50\text{--}15\text{ mm}$	Cross-linked macro structure retains same characteristics as the tire; irregular shape; some thermal degradation, temperature stressed. May exhibit nominal degree of reduced cross-linking	Product: Virgin rubbers, EPDM, CE: clay, sand, gravel, fly ash from coal burning polyurethane
Cryogenic	$\pm 0.5\text{--}5\text{ mm}$	Clean surfaces, regular particle size and shape, glossy, smooth surface, no surface decomposition or thermal stress	
Powder	$<1\text{ mm}$	Dependent on technology: ambient/cryogenic characteristics as above	Virgin rubber, EPDM, other compounding materials
Fine powder	$\pm 0\text{--}500\text{ }\mu\text{m}$	Most often produced by specialized treatments as below	Virgin rubber, EPDM, RCB, filler
SPECIALTY MATERIALS		DEPENDENT UPON PROCESS	
Reclaim	av.0.360 mm	Some characteristics of virgin rubber, limited aging and deterioration or flex fatigue; resistance easily modified during processing, improves flow, mold filling, lower die swell, can be added to virgin rubber and revulcanized	Virgin butyl rubber, EPDM, other commercial rubbers
Devulcanizate	$<1\text{ mm}$	Some characteristics of virgin rubber, increased surface reactivity, good fatigue properties, improved tensile strength, reduced cross-links, permanent elongation $<50\%$	Virgin rubber, EPDM

TABLE 26.6 Summary of Material Characteristics—cont'd

Material	Size	Key Characteristics	Traditional Materials
Surface modified	<1 mm	Activated surface gives improved cross-link density, permanent particle modification, return of some virgin characteristics allowing bonding with matrix during revulcanization	Virgin rubbers, EPDM other commercial rubbers
Pyrolytic char	<0.4–1000 μm	Coarse particles until treated, some structural change possible <i>Dependent upon process</i>	Carbon materials, fillers, coal burning residues
TPE	<1 mm	Mechano-physical characteristics similar to TPEs, about the same shore hardness and polymer base or virgin TPEs	Virgin rubber, TPEs, virgin plastics
Carbon products	>250 nm	Similar size, shape, surface area, structure, and dispersion as standard carbon blacks, all particles <30 μm , 50% <1 μm , can be used to replace N550, N660, N770	Traditionally produced carbon blacks

have maintained a relatively steady pace, with nominal glitches along the way. In general, there has been some expansion into new realms, while older markets are stabilizing and in some cases decreasing somewhat. There are strong indications that growth in new markets could continue.

Following are the six large traditional markets for RTMs which account for >75% of the materials produced. It is important to note that several markets utilize a range of different materials and, that over time, many of the markets have begun to overlap with parallel products and applications.

1. *Civil engineering and environmental management (CE, EM)* utilize primarily larger materials particularly whole tires, bales, shred, and chips. These treatments and applications are especially appropriate for coastal areas, countries/regions with erosion issues, as well as for landfill engineering and road construction bases. These markets have also grown to accommodate communities

with small quantities of tire arisings or limited budgets. Development prospects are positive, particularly as motorization continues to expand in new areas. Civil engineering is one of the first markets to absorb new arisings.

2. *Construction (CU)* utilizes a wide range of materials from shred and chips to granulate, powders, and even steel and textile fibers. During the past decade, construction has become one of the largest markets for RTMs as raw materials, ingredients, and products. Shred and chips are used for lightweight fill or backfill at construction sites. Granulate is the base for one of the most prevalent products, rubber sheeting made from 90% granulate, for noise and vibration insulation under various types of flooring or concrete screed. A second group of products uses rubber powder in the production bitumen sheets for roofing underlayments and mastic linings under tiles. Recently recycled steel fibers have been used as concrete reinforcement for industrial pavements,

concrete slabs, and spray concrete. Powders are used in glue mixes for ceramic tiles and plaster.

3. *Sports and leisure infrastructure management (SLIM)* has been a principal market for granulate accounting for large quantities in sport surfaces, playgrounds, and playing fields. International and national bodies have provided crucial financial support for these facilities for young and old in urban, rural, and isolated areas around the world. The fields reduce isolation and improve socialization, often in war-torn areas. As centers have flourished, slim projects have overlapped with other construction including buildings, parking areas, paths, marinas, and pool enclosures.
4. *Manufactured products (MFR)* are currently using large quantities of granulate and powders, and specialty powders to produce a wide range of consumer, industrial, and technical rubber products. These products range from solid wheels for trolleys and trams, to garbage cans, from shoe soles to gaskets, and many newly developed automotive products. Many products that are currently used in the automotive sector had their beginnings in other industries including tires.
5. *Urban transport (UT)* uses a wide range of RTMs for different products and applications.

Shred and chips are often used in road and rail beds, while granulate and powders are often used in rail housings and coverings. Virtually the same rubberized bitumen is used to pave around the transport area to provide noise and vibration dampening. It is important to note that during the past 5 years, there has been a major focus on providing urban transport options which, due to legislation, must include considerations for noise and vibration reduction.

6. *Materials (ING)* used as ingredients in complex blends, mixes, and compounds including Thermoplastic elastomers (TPE). These materials have become among the most sought after ingredients for rubber alloys, adhesives, plaster mixes, paints, and bitumen additives to name a few.

The quantities of each output of RTMs by mass is presented in Table 26.7. It is important to note that in 2016–17, two material streams appeared for the first time in significant quantities: specialty powders consisting of recycled carbon black (pyrolytic char), devulcanizates, reclaim, thermoplastics, and so on, and steel and textile fibers.

Whole tires accounted for about 122,000 t. The quantity used for recycling has increased nominally each of the past 5 years with a total increase for the period of about 2% [9]. It is important to

TABLE 26.7 RTMs by Mass^a

Material/Product	Fraction (%)	Mass (t)	Principal Uses/Applications
Whole tires	10	121,600	Whole, cut or in bales for CE and/or construction, FS
Shred/chips	18	218,880	CE, drainage, landfill engineering, horse tracks, FS
Granulate	52	632,320	Molded products, sport /play surfaces
Powders	11	133,760	Road surfaces, Molded products, sheeting, and so on
Specialty powders	8	97,280	Pigments, paints, carbon black, tires, TPEs, and so on
Steel and textile fibers	1	12,160	Concrete, vibration/sound panels, construction

FS, feedstock.

^a These volumes do not include >30,000 t of OTRs that were processed in 2016–17.

note that in the EU, whole tires, shred, or chips destined for energy recovery are not included in calculations for recycling as they are most frequently delivered directly to the recovery facility and treated on site.

Approximately 20,000 t of tires were used to produce shred and chips, of which the majority were used for a variety of applications for civil environmental engineering, animal husbandry, and construction applications. The quantity of shred/chips produced has increased marginally during each of the past 10 years, with a total increase for the period of almost 8%.

By far, the largest quantities of tires are used for the production of granulate. The quantity has remained relatively stable during the past decade, although the ratio to other materials has changed. About 700,000 t of tires input resulted in about 300,000 t of clean material containing <5% of impurities, tiles, or metals. The granulate market has changed considerably over the past decade from the predominance of sports and leisure applications to a wider variety of applications shared with construction, urban transport, and molded products. Automotive products have begun to take a significant role.

Approximately 130,000 t of various size powders of clean material became available for use. Together, both categories of powders increased just under 5% during the past 5 years. However, the data available on this category are not complete. It is assumed that at least some of the material produced is being used in very small-scale undocumented niche markets while the bulk of the material is used in more traditional applications. The principal markets remain compounding for use in mainstream applications and in the preparation of innovative new materials.

Production and use patterns vary outside of the EU. In Canada, China, Japan, Korea, the USA among others, the production of shred and chips far exceeds that of granulate and powders combined. While civil engineering is more developed in these countries, and consistently consumes vast quantities of tire materials, a large portion

of shred and chip production is used as tire-derived fuel (TDF) in energy recovery facilities.

6 APPLICATIONS AND PRODUCTS

Markets for recycled tire materials have grown exponentially over the years. They have increased on the merit of the products primarily because they have demonstrated that they are the most appropriate and effective for a particular application. The fact that the material is easily accessible and often the most cost effective compared to traditional materials has also contributed to the expansion. Recycling-for-recycling's sake is no longer an issue. Examples of the applications are given in Fig. 26.5.

Whole tires are used in the EU, as *barriers* for motorways (see Fig. 26.5). This applies particularly to motorways located in rural areas or bordering residential neighborhoods. The barriers are often constructed on soft, marshy, or otherwise unstable ground which cannot sustain traditional construction designs and must rely on alternative treatments and materials. This application has been successfully used in the EU, particularly in Scandinavia, particularly in Finland. As the EU Directive on noise becomes effective, greater quantities of tires may be consumed by these low cost structures.

Artificial reefs, marine barriers, coastal protection systems, fish hatcheries, breakwaters, and sea fender systems have been successfully used since the 1960s particularly in the South Pacific and in Asia. Many installations require that the

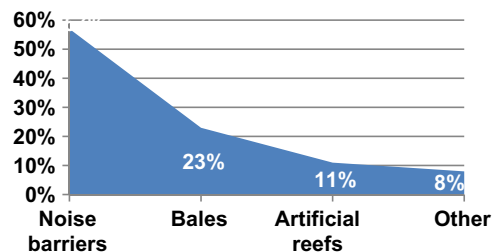


FIG. 26.5 Tires used as barriers to motorways.

tires first be filled with marine cement prior to construction to anchor them so that they will not break away. [10] Because of their inert structure, tires are easily colonized by algae, corals, and shellfish. Further, their open shape is an advantage when creating structures that require multiple niches where fish can hide from predators or breed. Research indicates that there is a limited amount of leaching of heavy metals and organic compounds. [10] The resilience and availability of tires has made them popular for building artificial reefs for fishery enhancement both in fresh and sea water. As greater emphasis is placed on coastal defense and the rehabilitation of damaged coastlines, more states may attempt to use them.

Bales have gained acceptance because they are lightweight in comparison to many traditional construction materials and can be used effectively to rehabilitate sensitive areas such as eroded slopes, waterways, and dams. They were first introduced into the UK in 2001. A bale is less than one-fifth the weight of cement, one-seventh the weight of gravel, and one-third the weight of packed earth, making it an effective alternative material for sensitive areas. They are nonbiodegradable, which has made them effective for long-term placement. Recently, they have been tested as replacement for gravel and riprap in roadway foundations and are being used for that purpose by the Army Corps of Engineers. A number of test sites have been built in the UK and have received support from local authorities [11, 12]. Bales could also be implicated in EU legislation concerning construction in sensitive areas which could help this developing market. Bales could have broad appeal for a variety of rehabilitative applications and could also be of particular interest to other island or peninsular regions specifically to overcome coastal erosion and defense problems.

6.1 Shred and Chips

Shredded tires and chips from tires are lightweight, relatively compressible and compactable, exert low lateral pressure, low thermal

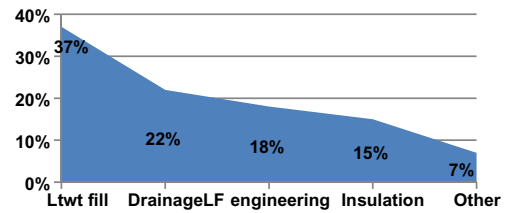


FIG. 26.6 The use of EU use of shredded tires and chips.

conductivity, and provide free draining in comparison to other materials. Fig. 26.6 illustrates the evolving markets for tire shreds and chips in the EU.

Shred is virtually nonbiodegradable even though exposed steel wires could begin to dissolve if continuously submerged below the water table in certain aqueous environments, depending upon the specific pH conditions. Studies indicate that even under those conditions, the exposed steel and zinc oxide leach only trace amounts at levels that are too low to be of concern. Based on its unique characteristics, shred has been used in numerous projects across the USA, Canada, Asia (particularly Korea), Australia, and South Africa. While the EU market is still small, it is growing solidly. Much of the ongoing research has been done at the University of Maine, at Orono [13], which was also instrumental in preparing the ASTM standard for the use of these materials. [14]

Lightweight fill is the largest market for shred. It is widely used in the base course for road and railway construction, as the shock absorbing layer for sports surfaces and more recently as the base for pipeline fields. Shred is used to stabilize embankments and bridge abutments, particularly on weak compressible or clayey soils. It is the primary alternative to traditional materials such as expanded clay, LECA and quarried aggregates, shale, soil, or gravel when excess weight could lead to instability. Used as backfill for retaining walls and bridge abutments, shred reduces pressure on the wall reducing settlement and cracking. In some communities loose fill is used as a covering on playgrounds to reduce injury from play or falls. Its principal

benefits are the ability to reduce weight, stress, noise, and vibration, which are key concerns within the EU. These markets have expanded by almost 25% during the past 7 years with indications that they will continue to grow (see Fig. 26.6).

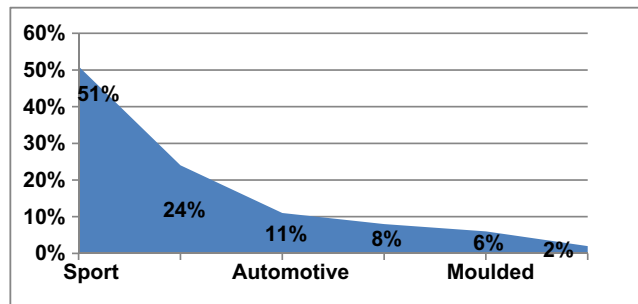
Drainage is of strategic importance, particularly adjacent to motorways and feeder roads, at road entrances and on curves or inclines. Almost all permanent surfaces, including sports fields, playgrounds, and so on, require appropriate drainage to maintain the integrity of the surface. Shred provides excellent free draining so that water pressure does not build. Filter drains, commonly referred to as 'French drains,' traditionally use graded aggregate or stone as the filtering agent. They are most often used along regional road networks to prevent the buildup of water at the side of the road and deter it from washing across the road surface, particularly during heavy downpours. When placed in layers below the road surface, the water is carried away and allowed to percolate into the soil. Traditional materials have a high risk of scatter due to vehicle overruns. Shred has been substituted for these materials with the added benefit that damage to vehicles is limited when the material is freed and becomes airborne. Other filter systems utilize a bitumen coated layer of shred under the loose material to control water flow. These very basic systems have been used in the EU since the mid-1980s but appear to have had limited growth in recent years. [12] (see Fig. 26.6).

Landfill engineering provides six separate opportunities for the use of shred in strategic operations: construction of a new cell, closure of a cell, daily cover, drainage layers, leachate collection, and gas drainage systems. Each of the applications relies upon the unique physical and technical properties of the material. The principal requirements are nonbiodegradability, light weight in comparison to traditional materials, relative compressibility, high permeability, low density, high void ratio, low lateral

pressure, low thermal conductivity, and free draining. The shred allows the rapid discharge of water and gas, and the reduction of the load on the landfill. The EU Landfill Directive specifies the structure to be used for the closure of a landfill, including the required water permeability. The physical properties of postconsumer tire cuts, shred, and chips are between 10^{-1} and 10^{-3} ms^{-1} , well within the minimum criteria of ($>10^{-3} \text{ ms}^{-1}$ [12]. In addition, shred can be used in the surrounds and to construct haulage roads. Landfill engineering has been particularly successful in Scandinavia and is being considered for use in several other States. The principal drawback is the reluctance of governments to use materials that are defined as waste in this manner (see Fig. 26.6).

Insulation from frost penetration, vibration, and sound are key benefits from shred in a variety of applications. The material reduces frost penetration beneath roads, and under outdoor sports surface installations. The materials are readily compressible and compactable, providing good thermal insulation and preventing problems from frost and thawing, thereby reducing damage to road pavements and foundations. Shred cushions and insulates underground pipes from freezing during winter months. Shred was first used at test sites in Italy to reduce vibration and noise around train and tram lines. Due to its success, it is now a mainstream material that is commonly used as sub-ballast and has been introduced in other EU States. Shred was introduced in Finland for thermal and vibration insulation around the foundations of commercial structures in areas adjacent to railway lines and airports. Vibration and noise insulation are key EU themes and it would appear that these uses could continue to increase in future (see Fig. 26.6).

Fig. 26.7 illustrates the importance of granulate tire material in EU markets in 2017, highlighting the dominance of sport surfaces and growth of industrial, automotive, consumer, and molded products. Granulate is used

FIG. 26.7 The use of granulate in the EU.

by diverse industries, each of which places different demands on the material.

Sport and play surfaces include among others, hockey and soccer pitches, running tracks, tennis courts, artificial turf, turf dressings, equestrian areas, and children's playgrounds. Among the key requirements for use in these structures are color, compressibility, durability, elasticity, free drainage, impact attenuation, low moisture content, porosity, as well as size and particle distribution. The use of granulate improves safety and absorbs the energy from impact. It reduces player fatigue, severity of injuries during play, and improves game response [15].

It is estimated that over 5,000,000 square meters of sports fields were built during the last 5 years in the EU alone, each of which can utilize approximately $14\text{--}15\text{ kg m}^{-2}$ of granulate as infill and/or top cover. In many states, legislation requires that primary school and municipal playgrounds are paved with shock absorbing materials, initiating a trend for using these surfaces at the >150,000 primary schools in the EU. Further, recent UN and EU legislation have provided funds for the construction of fields for young and old in urban, rural, and even isolated areas throughout the world.

It is important to note that the predominance of RTMs for sport surfaces have had a major impact on the reduction of serious injuries to players since they were first used. Over time, questions have been raised about the potential impact to human health and the environment

due to the materials. To date, ECHA, the European Chemicals Agency, and the United States EPA have supported this application.

Sports fields can be installed in a variety of ways, that is, with a solid surface, with a grass-like carpet, as artificial turf or with a loose unbound surface. The base can be constructed on gravel with 100% rubber infill, on a gravel base with a sand/rubber mix-infill, or on an elastic layer with a sand/mix infill. For solid surfaces, the materials are commonly bound with moisture curing polyurethane material or a polymer modified bitumen. Different size granulate is required for each part of the structure and depends upon the ultimate performance criteria of the surface. At times, shred is used as lightweight underfill. The surface materials can be wet or dry mixed, in situ or prefabricated into tiles or sheets of varying thickness and design to meet the requirements of the particular sport.

Outdoor running tracks are generally constructed with three layers including a base course and a solid surface, both made with granulate and bound with a polymer modified bitumen. They are used by schools for exercise and races.

Equestrian arenas, other than practice areas which often use loose clean chips or large granulate, are generally constructed with a solid surface. As most injuries occur on entry paths, new materials have been sought. To alleviate the problem, special blocks incorporating granulate

have been developed and installed in Alberta, Canada and have successfully eliminated the threat. The blocks have recently been introduced into the EU.

Industrial products and applications include a diverse array of products including flooring tiles, roofing materials, sound absorption products, soil treatment products, animal mattresses, vibration mats, and solid wheels for industrial equipment, as well as materials and products related to road construction, among many others. The markets are so diverse that there are no common material specifications. It has become apparent that the addition of granulate in all of these products does improve one or more performance characteristics of the final product. However, due to space limitations, only a few categories of products will be discussed.

Roofing and flooring tiles were among the earliest products made from granulate. They are still produced by mixing the granulate with polyurethane, placement in molds, and then heat setting. The resulting product has low tensile and tear strengths and high abrasion values. They are appropriate for use in outdoor installations and in heavily trafficked areas. In the EU they have become a choice for garden paths and patios.

Road construction including surrounds, parking areas, road furniture, traffic guidance systems and even manhole covers, utilize large quantities of granulate. Many road construction projects utilize different material categories for different parts of the structure, that is, bales for foundations, lightweight fill for embankments or for subbase drainage layers and granulate for the surface course. The well-documented benefits of granulate additives include: longer life, blacker pavements, good temperature susceptibility, better adhesion, increased elasticity, improved drainage, and reduced reflective cracking. Roads surfaced with asphalt rubber also reduce vibration, skidding, fog buildup and reflective glare, as well as reducing noise and frost penetration. Thus, rubberized asphalts could be of particular value on

small winding roads, in mountainous regions, 'quiet zones' near hospitals, and so on, as well as surrounding historic sites where vibration is one of the principal causes of damage [16].

Rubberized asphalt can be installed in a number of different ways: gap graded, open graded, SAMI, chip seal, or porous asphalt. Gap and open grading are surface course applications. Porous wearing courses are also surface applications, which increase friction while decreasing noise. SAMIs are surface maintenance treatments, used as an added layer for worn roads in order to prevent reflective cracking. Improved mixing procedures have reduced the cost of these applications so that they are now cost competitive with other materials. The materials have demonstrated that they are longer wearing than traditional materials.

In Australia, Canada, and the USA, among other areas, road surfacing applications consume the largest amounts of granulate. It would appear that the benefits far outweigh the disadvantages of using these materials. They add up to a smoother ride for drivers and lower maintenance costs for municipalities. However, rubberized asphalt has remained a very limited market in the EU, with few public authorities supporting investment outside of Spain, France, the UK and increasing test areas in the Netherlands, Belgium, and Italy. Nonetheless, it is anticipated that the impetus of the Circular Economy support for Green Public Procurement could serve as a stimulus for development and provide assistance in preparing projects that could improve the roads in many communities. A key consideration is the option to use these materials in historic centers where vibration could have negative impacts on monuments, and so on.

6.2 Powders and Specialty Powders

Fig. 26.8 illustrate the applications of powders and specialty powders and provides estimates of the quantities based upon reports from a range of innovative applications.

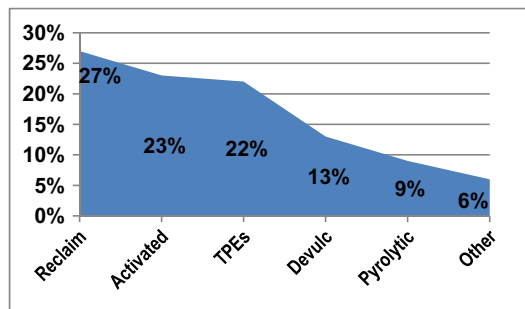


FIG. 26.8 Applications of powders and specialty powders from tires.

Powders produced ambiently or cryogenically retain the characteristics of the technology that produced them. Thus, ambient powders retain their irregular shape as well as the cross-linked macro structure of the tire from which it was produced. Due to increased processing to attain the finer size, some thermal degradation may occur which could produce a nominal reduction in cross-linking. Cryogenic powders retain their smooth, glossy, even shape and show no evidence of surface decomposition or thermal stress.

These powders from tires have been successfully used in coating materials for roads as well as for sprayed-on coatings and sealants. A unique process has been developed in which the powder is added to a solvent in order to form a rubber suspension. The material is used for waterproofing and can be painted, sprayed, or dipped.

Specialty powders include reclaim, surface activated materials, thermoplastic elastomers, devulcanizates, pyrolytic materials, and hybrid materials which are labeled "other." Overall, this category of material is the most uncertain in terms of actual quantities produced or used in products and/or applications.

Unlike the materials in other categories which are selected for use in specific products or applications, a majority of the powders and specialty powders are not used directly. They are ingredients selected for their specific contributions to

compounds, to then be mixed or blended with virgin materials for inclusion in an array of different types of products.

Reclaim is one of the oldest materials capable of restoring some of the characteristics of virgin rubber to recycled material. The addition of reclaim improves the flow of the new compound to facilitate mold filling, after which it lowers die swell. The new compound can be revulcanized. The largest market for reclaim is new tire production. It is used as an ingredient in the inner liner and can also be incorporated into the under-tread compound. It can be added to virgin rubber compounds and then revulcanized. It is often used in compounds for a range of molded products. Significant quantities of up to 75% of reclaim are used in the soles and other elements of footwear. The hardness, tensile strength, and elongation at break contribute to the ease of molding and are said to add to the durability and comfort of wear.

Surface modified or activated materials have a highly structured surface so that a high cross-link density can be developed, allowing it to be used in new rubber products. Key characteristics of the material include: high density, high resistance to abrasion which can increase the overall resistance of the vulcanized material, high tensile and tear strength and good elongation at break. It can be used as an active filler to substitute for virgin rubbers because the high cross-link density bonds with the surrounding matrix during vulcanization. Surface modified powders are an active ingredient in shoe soles and other consumer and industrial products and applications. They are increasingly being selected for use in automotive parts. Step plates for vans have recently been added as a product with considerable potential.

Thermoplastic elastomers (TPE) represent a new group of compounds that combine the material qualities of powders with the processing behavior of thermoplastic. The key characteristics include: tear and tensile strength, elongation at break, hardness, heat loss, heat deflection

temperature, impact resistance, rebound elasticity, bulk density, and dynamic modulus. The most important among its special quality parameters are permanent elongation distinctly below 50%, with approximately the same shore hardness and polymer base as traditional thermoplastic elastomers. Both the odor and the color can be altered to comply with customer specifications.

TPEs are used in a wide variety of products and applications including sheetings and linings, molded products including shoe soles. They are widely used in the automotive industries for under-hood elements such as o-rings, housings, and so on, and for molded interior accessories such as cup holders, and so on.

Devulcanizates are materials that have been reactivated, reducing the cross-links to restore some of the characteristics of virgin rubber—they are not totally devulcanized. Postconsumer tire materials can be partially devulcanized using several different methods, each of which will leave its mark on the final material, for example, chemical activation agents can change some of the physical and/or chemical properties of the resulting material. Key characteristics include: hardness, low density, decreased surface reactivity, good fatigue properties, improved tensile strength, and permanent elongation of <50%. Devulcanizates are used for many industrial products and most recently for tire production.

Examples of recycled tire material applications are given in [Table 26.8](#), providing an estimate of the quantities of tires and recycled tire materials required to produce a broad sample of products and applications. The examples below reflect the basic profiles of over 500 products and applications in mainstream markets today that utilize RTMs.

7 ENERGY RECOVERY

While energy recovery is not recycling, and does not benefit from multiple reuses of regenerated materials, it is a crucial part of attaining

sustainable development goals. Thus, no discussion of tire recycling would be complete without mentioning energy recovery.

As material recycling, energy recovery is inextricably linked to the prevention and minimization of waste. It is one of the two principal means of valorizing the waste that does occur and, thus reducing its environmental and economic impacts. Together, material recycling and energy recovery offer alternative and complementary means of gaining the greatest sustainable benefit from natural resources and their wastes, thereby reducing the consumption of virgin resources.

Between 35% and 38% of tires in the EU and about 45% in the United States are used as a supplementary nonfossil fuel in some form of energy recovery process in cement kilns or in incinerators to generate electricity, steam, and so on, replacing other energy sources. Every country involved in tire recycling has developed at least one technology for incineration with energy recovery. Recent developments which permit the use of mixed feedstock, that is, tires mixed with other postconsumer or production materials, ensure continued interest.

Tire-derived fuel (TDF) is a broad rubric which includes whole tires, tire wastes, cuts, shred, and chips. It is used extensively in developed as well as developing regions around the world. In Japan and the United States, among others, energy recovery is the foremost means of valorization of postconsumer tires and industrial wastes.

8 THE FUTURE

Tire recycling has two, at times mutually exclusive missions. First, under existing International and EU legislation, it is a waste management industry responsible for every aspect of the waste management function related to non-roadworthy tires. As such, it must respond to numerous and at times onerous regulations that cover every aspect including permitting for waste

TABLE 26.8 Examples of Recycled Tire Material Applications

Application	Approx. Quantity	Approx. Unit of Application	Format
Sea embankment	3000 car tires	500 m × 1.5 m high	Whole
Sound barriers	20,000 truck tires	1 km × 3 m high	Whole/cut
Artificial reef	30,000 car tires	1 km × 1 m high	Whole/bale
Drainage culvert bed	50,000 tires	1 km long	Whole/cut/bale/shred ^a
Coastal stabilization	2000 bales	1.3 m high × 1 km	Bales
Embankment	1,000,000 car tires	330 m × 3 m high	Shred (compacted) ^a
Backfill	80–100 car tires	1 m ³	Shred (compacted) ^a
Bridge abutment fill	100,000 tires	1 m wide × 200 mm	Shred (compacted) ^a
Lightweight fill	2700–3600 km m ²	Layer thickness ± 1–6 m	Shred (compacted)
Tram rail beds	50,000 tires	1 km	Shred (compacted) ^a
Equestrian track	15 tires	10 m ² with 15 mm thick	Shred
Thermal insulation	300,000 tires	0.3 m thick × 10 m wide	Chip/shred ^a
Drainage layer	300,000 tires	0.3 m thick × 10 m wide	Chip/shred ^a
Road surface	70,000 tires	1 km 1 lane road	Granulate
Play surface (25 mil)	1400 tires	~500 m ²	Granulate
Asphalt rubber	3500 tires	1 km × 12 m × 0.05 m	Granulate
Animal mattresses	18 tires	Unit	Granulate
Sound barriers	20,000 tires	1 km × 3 m high	Granulate
Running tracks	2700 tires	400 m × 7 m	Granulate
Infill for artificial turf	12,200 tires	Normal field	Granulate
Safety tiles	4 tires	1 m × 1 m × 0.04 m	Granulate
Elastic layers	3 tires	1 m × 1 m × 0.03 m	Granulate
Mats or sheets	1 tires	1 m × 1 m × 0.01 m	Granulate
Solid wheels (carts)	approximately 1 t of tires	about 900 units	Granulate/powder
Antistatic shoe soles	1 tire	6 shoe soles (adult)	Powder
Pigments	112 tires	30–50 pigments	Powder

^a Quantity of tires depends on producer's formula and specifications BRRC, BioSafe, ETRA, D. Humphrey, La Sapienza.

transport, storage requirements and restrictions, as well as environmentally sound valorization.

Second, tire recycling has evolved into a commercially successful industry which has become increasingly profitable for SMEs. It must provide

materials and products which meet commercial demands and performance specifications, cost effectively.

From virtually every perspective, the tire recycling industry has made great strides during

the past 25 years. By all indications, it is successfully meeting the demands of International and EU legislation and mandates in terms of treating waste in order to produce viable materials, and then using the materials in applications and products. Further, today, those materials are being produced in a sustainable, environmentally sound context and are effectively used to substitute virgin materials for increasingly diverse markets—without substituting quality. In many instances, the characteristics and properties of these materials contribute to improved performance, often more cost effectively. Many have taken their place in the mainstream even though they are still considered waste. Even recycling residues are treated and used in innovative ways.

From 1992 through to 2017, tire arisings within the EU Member States totaled over 80×10^6 t (80 million tonnes). Of this, almost 20×10^6 t were materially recycled into an array of materials, applications, or products as discussed in this chapter. It is important to note that in 1992 material recycling accounted for a mere 5% of total arisings or $<100,000$ t while in 2017 material recycling had grown to 38%, or approximately 1.5×10^6 t per year with uncounted tonnes recycled from off-road tires.

Efficient, effective material recycling produces vast savings in terms of material and energy. Energy in different forms is a crucial part of each phase of a product life cycle—from the production of raw materials, to manufacturing, distribution and use, through collection during the waste phase, and, finally, for recycling and delivery of sustainable products to market. In addition to providing clean, cost-effective, environmentally sound, and durable materials for 50 industry sectors, the recycling of postconsumer tires contributes to the EU goal of a recycling society, with reduced reliance on energy inputs.

A few simple facts about the energy used for tires, tire rubber and recycling, measured in barrels of oil, or tonnes of oil equivalent (toe):

- Manufacture of one tonne of tire rubber requires 3546 L (22.3 barrels) of oil, or 125×10^9 J (3 toe) of energy
- Manufacture of one tonne of recycled tire material requires only 64 L (0.405 barrels) of oil or 21×10^6 J (0.52 toe) of energy
- The energy recovered from one tonne of tires is only 836 L (5.26 barrels) of oil or 30×10^6 J (0.72 toe) of energy

In terms of *energy* alone the savings that accrue from material recycling, about 15×10^6 t of tires, rather than manufacturing the same amount of new tire rubber, or using tires for “energy,” are equivalent to:

- about 6400×10^6 L (400 million barrels) of oil
- That amount is somewhat >2 full years of daily oil imports for seven Member States (*Bulgaria, Cyprus, Estonia, Hungary, Luxembourg, Slovakia, Slovenia*)
- Or ± 800 days of oil imports for Greece (more than 2 years)
- Or numerous trips circumnavigating the globe (31.45 barrels per trip)

Each tonne of tires materially recycled equals a savings of an equivalent of about 3260 L (20.5 barrels) of oil in energy costs for production alone. The difference in energy use between manufacturing one tonne of new tire rubber and recycling one tonne of tire rubber is equivalent to about 3320 L (20.9 barrels) of oil.

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Medical Waste

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1 INTRODUCTION

This chapter provides a general overview of regulations and issues relating to the generation, storage, treatment, and disposal of regulated medical waste, generally referred to as health-care waste (RMW/HCW) in the United States, the United Kingdom, in Europe, and elsewhere. The goal is to provide a comprehensive definition of what is generally considered to be RMW/HCW and how it should be packaged, transported to its next destination for treatment and/or final disposal.

The management of RMW/HCW is generally heavily regulated from the point of generation to the point of disposal. The amount of legislation and the influence the regulatory agencies of each government have on the management of health-care waste tends to be in line with legislation or regulations for other areas, not just waste. Where there is a significant regulatory burden for all aspects of society, there will be systems and guidance in place that are expected to be followed. In those areas, penalties will be applied to those who do not manage waste in line with the regulations. Where the regulation does not exist, or exists, but compliance is not enforced by the regulatory agencies, there are issues with correct and safe management of these wastes, many of which have the potential to cause serious harm.

Regulations promulgated in the United States began with increased public awareness of reported adverse pollution events in the late 1980s and improved awareness regarding infection control and safety practices in the handling of this waste stream, thus the US Environmental Protection Agency (EPA) instituted the Medical Waste Tracking Act of 1988 (MWTa) [1] for 5 years. The US Occupational Health and Safety Administration (OSHA) subsequently developed occupational health and safety standards addressing the hazards associated with blood-borne infectious diseases

(pathogens) that may be of concern in the promotion and maintenance of the health and safety of employees in the workplace [2]. Similar legislation was developed in parallel in other parts of the world, although not necessarily in the form of single regulations. In a number of countries, several pieces of legislation may have an impact on the management and movement of these waste types. For example, the US Department of Transportation Pipeline Hazardous Materials Safety Administration (DOT PHMSA) promulgated regulations for the safe and proper packaging for transport of RMW and has continued to adopt changes as the United Nations (UN) changed regulations for Europe. There are a number of other pieces of environmental and health and safety legislation that have driven forward improvements in the way that healthcare waste is managed. Legislation, coupled with the general public becoming more aware of the risks of mismanaged waste through news and social media, has led to pressure on healthcare waste producers and waste contractors to review their processes and ensure healthcare waste is managed appropriately from cradle to grave. This is not always the case in low- to middle-income countries and there are still occasional issues in areas where there is an expectation that waste will always be managed in line with the regulations and public expectation.

Recent research has shown that 53.9% of domestic waste handlers and 75% of RMW/HCW handlers have received some sort of sharps injury. Sharps injuries are classed as needlestick or cut wounds. In Thailand 77.4% of domestic waste workers reported at least one sharps injury and in Ethiopia, 19.8% of all accidents to all waste workers were attributed to sharps injuries. This rose to 43% for healthcare waste workers [3].

The main barriers to correct and safe management of RMW/HCW include but are not limited to:

- the lack of appropriate and available financial and technical resources,
- inadequate or nonexistent regulatory frameworks,
- lack of information and training,
- improper disposal of RMW/HCW in underdeveloped rural areas,
- mass migration to areas without infrastructure,
- epidemics/pandemics.

2 REGULATIONS

2.1 Regulation in the United States

As stated before, EPA MMTA of 1988 was enacted by US Congress in response to increased concern regarding potential health hazards that may be caused by untreated and improperly disposed RMW/HCW, both generated in the public and private sectors. Ultimately, the EPA determined that the infectious components and risk of exposure were highest at the point of generation (hospitals, medical office, etc.) and that the RMW itself was not a long-term environmental threat. EPA no longer regulates RMW under its enforcement authority or under the Resource Conservation and Recovery Act (RCRA) as a hazardous waste; it is considered a solid waste under EPA.

Responsibility for promulgation of regulations and enforcement jurisdiction was ultimately relegated to the individual states within the United States. Individual state government representatives chose to promulgate legislation and subsequent regulations as they deemed fit for their state related to management and standards for treatment. As of 2017, the majority of US states have enacted regulations regarding the handling and disposal of regulated medical waste. Many regulations have been modified throughout in recent years to modernize and account for the changes in the medical waste management industry. Historically, many healthcare facilities,

schools, and other institutions had on-site incinerators which were able to accommodate the wastes generated on-site and from surrounding small facilities. Since the passage of the EPA Clean Air Act and subsequent regulatory restrictions on Hospital Medical Infectious Waste Incinerators (HMIWI) in 1997 (and in the most recent modification of the regulations in 2009 and implemented by 2014), 98% of these incinerators have been shut down. The majority of waste is now shipped off-site from generating facilities and is managed at professional, commercial, medical waste management facilities using alternative technology such as autoclaving. However, this method of state adoption of varying degrees of regulatory restrictions has created a patchwork of requirements, making the management of RMW/HCW challenging in the United States.

The change in the management of wastes off-site prompted the DOT to look more closely at ensuring safe transport of these materials on public roads. In 2006 DOT PHMSA passed additional regulations harmonizing with UN regulations. PHMSA regulations outline the criteria for packaging material, labeling, shipping documents, and training for employees for all commercial carriers of RMW/HCW in the European Agreement for the transport of dangerous goods (ADR). It is a preemptive regulation providing for consistency in the industry for transport of these wastes.

2.2 Regulation in the Europe

All waste generated in any healthcare establishment across Europe is defined as Health Care Waste. However, not all this waste is treated as hazardous waste. Waste should be segregated at the point of generation based on the hazardous characteristics at the point of production [4]. There will be a large proportion of the waste that has no hazardous properties and will be disposed of as domestic-type waste. The World Health Organisation (WHO) estimates that 10% of this waste has the potential to cause

infection, injury, or other health impact. A further 5% is classified as hazardous waste that may have chemical (or pharmaceutical) or radioactive hazardous properties [5]. Very few member states have specific healthcare waste regulations, as these waste streams are complex and falls into the remit of a number of directives and European Regulations. European Directives are statutory instruments that require member states to transpose them into their own legislation while achieving a certain legal standard. European Regulations are statutory instruments that impose legal standards onto all member states and these take precedence over any domestic legislation. Examples of these are the Hazardous Waste Directive which provides the legislative framework for the collection, transport, recovery, and disposal of waste and also includes a common definition of waste.

The complexity of the legislation has meant that systems for the management of HCW have evolved steadily over time to meet the regulatory requirements, but so far there has been little emphasis on waste minimization and implementation of best practice. Sustainability is entering the vocabulary of healthcare professionals, but it still firmly rooted within energy and water consumption rather than waste prevention and minimization.

2.3 Worldwide Concerns

Although current regulations and controls over this waste stream vary around the world in complexity and efficacy, several key concerns remain ubiquitous in the consulted literature, including, but not limited to, the following:

- *Treating large volumes of waste as RMW/HCW.* Even though many RMW/HCW wastes may not be infectious in nature and could be safely disposed of as general waste, there are still many misunderstanding surrounding final disposal. These include items such as used latex gloves, gowns, cardboard, and other items that may be generated in a health facility that do not pose a risk to public health. In fact the disposal of these items as medical waste and require them to be treated may pose more of a risk to public health and the environment during the treatment process (for example through the release of dioxins during incineration). In some member states in Europe all wastes from hospitals are sent for incineration at energy from waste facilities whether hazardous or not. Other member states may use a range of treatment methods, some of which encourage better segregation more than others.
- *Failure to reduce overall waste.* Creating and instituting improved policies and procedures regarding the proper use of single use or reusable items and identifying recycling options would help the overall waste generation. Key in this action would be the education of healthcare workers on proper waste management and practices. Engagement with the circular economy agenda will assist with reducing the volumes of healthcare waste generated. There are items that are nonhazardous that could be diverted from unnecessary treatment prior to final disposal. Examples include clean packaging, clean tray wrap used in theaters, and so on.
- *Education for all.* Part of the challenge of improving waste management of RMW/HCW is misconceptions people have and lack of education or awareness of what is really hazardous vs what is not. Specifically, the education of healthcare providers on the proper segregation and disposal of different types of wastes would be very beneficial in proper infection control and waste reduction. Today healthcare professionals are not educated through their normal courses on segregation and management of waste. This has to be part of their normal course load through schools, universities, and professional development. This would ensure consistency in the way wastes are generated and subsequently managed.

- *Education of the public and private sectors regarding potential hazards of exposure to contaminated waste:* In many cases the general public is unaware of the real risks of the different types of wastes generated at healthcare facilities. Often, the public thinks that all waste from these facilities is hazardous and often demand of their political and local representatives to properly protect them from such facilities in their community. This means that facilities which existed in communities that operated safely for years servicing the healthcare communities now are in jeopardy because communities have started to grow around them. The fact is communities continue to shun waste management facilities, improperly assuming that they are harming their communities, thus making it harder for facilities to exist and more expensive to operate and maintain because they are farther away from the wastes being generated. Educating the general public and communities about the benefits that waste facilities bring and that they actually help protect the environment from potential infection rather than the other way around would make facilities more viable.
- *Public Sharps education:* Lack of government and organizationally sponsored funding for public sharps disposal programs. Failure to institute these programs leads to higher exposure rates to the public, sanitation workers, and landfill workers to hazards associated with needle stick injuries.
- o. Where sharps waste is not being formally collected in approved and labeled containers, advice is still to collect them in sturdy containers with a lid, such as detergent or milk bottle. As these have a value for recyclers, it is easy to see how the contents can cause injury to those coming into contact with them. This is a global problem, not just limited to developing nations [6].
- *Hazards from Drugs:* Increasing new types of drugs and treatments that may not have not only infectious risks, but also chemical. Hazardous drugs such as chemotherapy and radioactive treatments can create a risk to the healthcare worker while administering the medications, but if not properly educated on the proper disposal can cause risk for all workers downstream. Hazardous drugs also pose a risk to the environment if not properly managed, affecting the drinking and ground water for many and potentially affecting both human and wild life.
- *Waste Classification:* Correct classification can reduce the quantity of waste that needs to be sent for specialist treatment and increase the quantity that can be diverted to more environmentally friendly treatments and recovery processes.

3 DEFINITIONS OF RMW AND HCW

3.1 Definition of RMW in the United States

Although variations of what is considered to be RMW do exist among states within the United States, the basic designation of waste types considered to be part of this waste stream was developed using guidance established by the MWRFA of 1988. The following are examples of definitions adopted by several Federal or State legislation or regulations:

- Cultures and stocks of infectious agents and associated biologicals, including laboratory waste, biological production wastes, discarded live and attenuated vaccines, culture dishes, and related devices.
- Blood and other bodily fluids: Liquid human and animal waste, including blood and blood products and body fluids such as serum, plasma, emulsified human tissue, spinal fluids and pleural and peritoneal fluids, but

not including urine or materials stained with blood or body fluids.

- Pathological waste tissues, organs, and body parts, carcasses and body parts of all animals known to have been exposed to pathogens (intentionally or naturally occurring) affecting humans.
- Regulated medical waste, clinical waste or biomedical waste means a waste or reusable material derived from the medical treatment of animal or human, which includes diagnosis and immunization, or from biomedical research, which includes the production and testing of biological products.
- Sharps: any object contaminated with a pathogen or that may become contaminated with a pathogen through handling or during transportation and also capable of cutting or penetrating skin or a packaging material. Sharps includes needles, syringes, scalpels, broken glass, culture slides, culture dishes, broken capillary tubes, broken ridged plastic, and exposed ends of dental wires.
- Decontamination: method of treatment that results in the reduction in concentration of microorganisms or biological toxins of concern to a level considered safe for handling and disposal.

3.2 Definition of HCW in Europe

In Europe there is a single classification system for all wastes that depends on the properties of the waste; this is known as the European Waste Catalogue (EWC). Healthcare waste falls within Chapter 18 of the EWC. There are 15 hazard properties identified in the Annex III of the Waste Framework Directive (2008/98/EC) [4]. Wastes that are not domestic-type wastes fall broadly into two categories, waste that has the potential to cause infection and those that are

medicinal. These are the wastes that need to be treated to render them safe. Everyone who generates waste has a “duty of care” to ensure it is managed correctly from the point of generation; this means that those producing the waste have to dispose of it in an appropriate container that will be sent for correct disposal. There are a number of disposal routes that healthcare waste can take, depending on its hazardous properties. The properties most likely to be associated with cytotoxic waste include properties such as acute toxicity, infectious, carcinogenic, toxic for reproduction and ecotoxicity. Other pharmaceuticals and chemicals used in the healthcare sector may have flammable or acutely toxic characteristics, for example and also have infectious properties which complicates disposal.

Hazardous wastes include infectious waste, some pharmaceutical waste (cytotoxic/cytostatic), fluorescent tubes, specified chemicals, oils, batteries, waste electronic and electrical equipment (WEEE), asbestos, paints, and solvents. Nonhazardous wastes include domestic-type waste, food waste, offensive/hygiene waste, packaging wastes, recyclates, and furniture [7].

There is an entire healthcare waste stream that consists of waste that may be contaminated with blood or body fluids that originates from patients that are not known or reliably suspected to have an infection that would render any waste generated as infectious. This is classified in European Waste Catalogue [8] as waste whose collection and disposal is not subject to special requirements in order to prevent infection (e.g., dressings, plaster casts, linen, disposable clothing, diapers) and is assigned the European Waste Catalogue number 18 01 04. These wastes may cause offensive by virtue of appearance or odor, but do not pose an infection risk. This is recognized by the fact that it is not classified as a hazardous waste.

4 ESTIMATED VOLUME OF REGULATED MEDICAL WASTE GENERATED IN HEALTHCARE FACILITIES AND TYPES OF WASTES GENERATED

4.1 Estimates of Types and Quantity of Wastes Generated Today

Hospitals have traditionally been noted as being a large generator of waste. There have been many efforts in the United States to reduce the overall volume of waste generated in healthcare, but there are some wastes that are unavoidable. RMW makes up approximately 15% of the overall volume of wastes generated in healthcare in the United States today which is in line with the WHO figure of 10% infectious and 5% contaminated with other pharmaceuticals or radioactive. There are more reusable instruments on the market today, but there are some materials that are difficult to disinfect appropriately to make them safe for reuse. Many states rely on commercial facilities to report volumes. Other states rely on the generators to report on their volumes to keep track of wastes generated by different types of healthcare facilities. However, there is no one entity that tracks total amounts. This makes it difficult to target and determine how best to manage these waste streams. While wastes may be classified under different regimes in different parts of the world, the characteristics tend to be similar.

The types of wastes that are regulated tend to be:

- blood or bodily fluid contaminated materials; infectious substance contaminated materials; this could include personal protective equipment (PPE), instruments, sharps, discarded specimens—can be treated via alternative methods and incineration;
- pathological wastes—some states require incineration;
- trace chemotherapy wastes: items like PPE, IV tubing and bags, sharps—some states require incineration;

- bulk chemotherapy wastes: bulk quantities of premixed or raw materials used for chemotherapy treatment—typically sent for hazardous waste treatment (hazardous waste incineration);
- nonhazardous waste pharmaceuticals: pharmaceuticals that are not considered a hazardous waste under EPA regulations but could still have a detrimental impact on the environment and public health—few states have requirement for incineration but most do not; some state or local jurisdictions do not allow for drain disposal;
- hazardous waste pharmaceuticals: pharmaceuticals that meet the conditions as a hazardous waste under EPA regulations—must be sent for treatment at a permitted hazardous waste facility (incineration or burial).

4.2 Types of Wastes Found in Different Facilities

Although [Table 27.1](#) represents a very limited picture of regulations worldwide, it provides an example of the tracking of different types of facilities that generate RMW/HCW. This data is not all inclusive but gives a rough idea of the types of wastes generated in different facilities.

5 FACTORS AFFECTING MANAGEMENT OF RMW/HCW

5.1 Packaging of Supplies

There have been a number of initiatives to reduce the volume of packaging produced by the healthcare sector. This must be taken in context as there is a need to ensure the integrity and sterility of the items being used for procedures. There is often a minimum of three layer packaging to ensure that the final layer is sterile and the items only exposed for use in close

TABLE 27.1 Commonly Regulated Medical Waste Producing Facilities and Wastes Generated

Facility Type	Types of Medical/Healthcare Generated Waste
Hospitals	I, II, III, IV
Physician offices	I, II, III, IV
Dental offices	I, II
Mortuaries	I, II, III
Veterinary facilities	I, II, IV, V
Nursing homes, hospices	I, II
Ambulatory, EMS services	I, II, III
Tattoo/body art	I, II
Transfer stations	I, II, III, IV, V
Treatment facilities	I, II, IV, V
Mental health facilities	I
Outpatient surgical facilities	I, II, III
County and university health departments and clinics	I, II
Dialysis facilities	I, II
Clinical and analytical laboratories	I, II, III, IV, V
Blood/plasma collection facilities	I, II
Industrial clinics	I, II
Universities, schools, and training facilities	I, II, III, IV, V
Prisons	I, II, III,
Laboratories	I, II, III, IV, V

Type I: Sharps (syringes, IV tubing with needles attached, lancets, scalpels, etc.) this will also contain pharmaceutically /chemically contaminated wastes that may require incineration according to national legislation or other regulations.

Type II: Blood, Body Fluids, and items saturated with Blood, Body Fluids.

Type III: Pathological Waste (human tissues, body parts, products of conception, tissues not placed in a fixative agent, organs removed during trauma, surgery, autopsy, or other medical procedure).

Type IV: Cultures and Stocks of Infectious Agents (laboratory waste, biological production wastes, discarded live and attenuated vaccines, culture dishes, and related devices).

Type V: Contaminated waste from animals subjected to pathogens infectious to humans, primarily originating from laboratory research testing.

proximity to the procedures taking place. Given all layers of the packaging are clean until the final layer, opportunities for recycling or reuse in nonsurgical applications should be investigated.

5.2 Extended Producer Responsibility

Extended producer responsibility (EPR) regulations across the EU with a number of member states including medical waste and old unused

medicines in their EPR schemes. In 2014 there were eight member states who included these waste types with a total of 240,000 tonnes of waste generated. To put this in perspective 25 out of 28 member states had EPR schemes in place for packaging which generated in excess of 78.6 million tonnes of material [9]. There are also take-back programs that are not formally recognized as EPR schemes such as medicines and sharps that are taken back to pharmacies and healthcare providers. These schemes are responsible for ensuring that pharmaceutical and sharps waste do not enter household waste streams and are treated correctly in line with national legislation. A number of nations require that pharmaceutical waste is incinerated or denatured to prevent reuse.

5.3 Transport

The transport of infectious substances was taken under the auspices of US Department of Transportation Pipeline Hazardous Materials Safety Administration (DOT PHMSA) promulgated regulations for the safe and proper packaging for transport of RMW. The UNECE Sustainable Transport and Environment Divisions, together with the World Health Organization (WHO)—Europe, coservice the Transport Health and Environment Pan-European Programme (THE PEP) through the European Agreement for the transport of dangerous goods (ADR) [10]. Forty eight member states of the UN have also signed up to use the principles of the document. This means that there is unified set of UN numbers, UN3291 is used for infectious waste that is known or reasonably expected to contain pathogens. In this context, pathogens are described as micro-organisms including bacteria, viruses, rickettsiae parasites, fungi, and prions which can cause disease in humans and animals.

All regulated medical waste/clinical waste must be packaged for transport in accordance with dangerous goods legislation. Healthcare waste that is classified as 18 01 04 [8], waste that does not require special treatment to prevent infection, is specifically excluded from all dangerous goods legislation as it not considered to pose a risk to those transporting it [10].

Waste that is assigned as UN3291 clinical waste, unspecified not otherwise specified (n.o.s) or (bio)medical, n.o.s, or regulated medical waste, n.o.s must be packaged and transported in tested and marked containers and under specific conditions. These conditions are stringent and are regulated by the competent authority in each country. Generally the packages used will be tested in line with the requirements of the legislation (ADR/DOT, etc.) and will be transported under national legislation. This has become more of a regulatory burden as waste producers send their waste to centralized treatment plant for incineration, where waste is treated on-site and does not travel in the public highway; there is no need to meet the stringent requirements laid down in the international agreements. It is also possible to send packaged RMW/HCW for international shipment by rail, air, or sea. Each of these modes of transport also has stringent requirements and the associated guidance (RID for rail, IATA for air and IMDG for sea) must be followed. If waste is being transferred between countries account must be taken of any transfrontier shipment of waste regulations.

US DOT regulations have slightly less stringent requirements yet still allow for reusable containers; however, it requires the proper cleaning of the containers before reuse. The integrity of the container still requires that it is leak proof and can withstand the general transportation.

6 APPROVED METHODS OF TREATMENT FOR MEDICAL WASTE (UNITED STATES AND EUROPE)

6.1 In the United States

In September of 1997, the US EPA adopted new source performance standards (NSPS) and emissions guidelines (EG) for hospital/medical/infectious waste incinerators (HMIWI), established under Sections 111 and 129 of the Clean Air Act (CAA) [11]. An HMIWI is generally defined by the EPA as a device used to treat wastes generated in hospitals or medical/infectious waste, a typical unit being a small dual-chambered incineration device that burns approximately 350 kilograms per hour (350 kg h^{-1}) of medical waste. Smaller devices may burn as little as 7 kg h^{-1} and larger units up to about 1650 kg h^{-1} . Prior to the adoption of these NSPS and EG in 1997, the majority of RMW treated in the United States was treated by incineration. Due to strict performance standards and emission guidelines as noted before, most of the medical waste incinerators in the United States have shut down since that time and other methods have been employed (autoclaving, microwaving, etc.). The EPA reported that in 1997 approximately 2300 HMIWI existed in the United States; in 2009 only 57 HMIWI were known to exist [12]. Today there are less than 35 HMIWI and only 14 of those are commercial facilities that are able to accept outside wastes. The other facilities are considered “captive” units which are not able to accept other wastes from outside their own facilities (universities and research operations for example).

6.2 In the United Kingdom and Europe

It is a similar story in the United Kingdom where hospital incinerators lost their Crown Immunity in 1992. There are a small number of clinical waste incinerators in the United

Kingdom now and the majority of those are operated on a commercial basis by external companies.

In Europe there are a number of energy from waste facilities that can utilize the energy contained within the waste to generate power. This approach does not fit strategically with a number of administrations and is not seen as the best use of natural resources. Some countries have a hybrid system with some wastes requiring incineration and some requiring an alternative form of treatment to reduce risk of infection. Where high temperature incineration is the preferred option, there are a range of other suitable technologies available.

6.3 Remnants of Waste Management and Treatment

Any remnants of RMW/HCW that remain following the incineration process (ash) are typically disposed of in sanitary landfills. Air pollution remains the most significant problem relating to the incineration of medical waste, as multiple pollutants can be generated from this waste stream either unchanged or as a result of the incineration process. The EPA identifies the following pollutants as being generated in the treatment of medical waste by incineration:

- particulate matter (PM)
- heavy metals, including lead (Pb)
- cadmium (Cd)
- mercury (Hg)
- chlorinated dibenzo-*p*-dioxins/dibenzofurans (CDD/CDF)
- carbon monoxide (CO)
- nitrogen oxides (NO_x)
- hydrogen chloride (HCl) gas
- sulfur dioxide (SO_2) gas

In October 2009, the Federal Register was updated, and new NSPS and EG were adopted for HMIWI with more stringent requirements, reducing permissible pollutant levels for these types of incinerators [11]. As mentioned before,

the adoption of these requirements has led to closure of additional HMIWI and lessened the likelihood of new incinerators being built.

The Healthcare Environmental Resource Center (HERC) recommends that the following pollution prevention and waste reduction methods be performed in order to alleviate the pollution risks associated with incineration of medical waste, which include the following [12]:

- Ensure that wastes are appropriately segregated at the source of generation to ensure that only wastes that are required to be incinerated by each governmental agency are actually sent out for treatment by incineration. This most often includes pathological waste and medical waste contaminated with trace amounts of chemotherapy drugs. Sharps may also be required to be incinerated or “destroyed” prior to ultimate disposal at a sanitary landfill by some regulatory agencies.
- Minimize the volumes of PVC plastics that are incorporated into this waste stream, including plastic packaging used in the healthcare field. This type of waste should be recycled whenever possible and eliminated from waste that is treated by incineration, due to the potential formations of dioxins during the process.
- Eliminate any mercury-containing wastes from this waste stream.
- Do not allow any wastes containing chlorofluorocarbons (CFCs) to be incinerated.
- Use alternative treatment methods whenever allowable under government agency regulations.

A significant issue that will arise with the elimination of HMIWI in the United States is a lack of devices capable of meeting current state regulations for treatment. As stated before some states require that pathological waste must be treated by incineration only, along with trace chemotherapy waste. Although most of the medical waste generated in hospitals and other

regulated facilities can be treated using alternative methods, legislation will need to allow for the future treatment of these types of wastes that is not incineration. However, consideration should be given to the type of waste and its potential impacts on the environment. Wastes such as drugs and chemotherapy wastes could still impact the environment if not properly managed.

6.4 Consideration of Management and Treatment Methods in the Future

Many nations require that any RMW/HCW treatment technology (i.e., not incineration or autoclaving) receive a review and approval from the state agency responsible for regulating medical waste prior to its installation and use in commercial treatment. In the United States, standards were developed by states following the MWTA of 1988 to utilize in the evaluation of these technologies by the EPA and other independent professional associations that are still used today in the approval process.

There are a range of technologies entering the market for the treatment of infectious and pharmaceutical wastes. The choice of treatment technology should be in line with national environmental strategy and also be suitable for local conditions.

There is a list of factors that need to be considered before selecting a healthcare waste treatment technology. These include:

- what healthcare is being delivered and how, field hospital, medical center, or state-of-the-art hospital,
- infrastructure, for example, road and rail networks,
- types of containers and vehicles used for transport,
- personnel and training available to manage waste and equipment,
- climate (temperature can have an effect on efficacy of treatment systems),

- fuel sources for treatment operations including electricity or natural gas,
- access to water and posttreatment water management,
- training in use of the technology for different types of treatment,
- waste segregation for treatment,
- maintenance and testing programs for different treatment technologies,
- pollution control for different treatment technologies (air, remaining solid waste, and water should be taken into consideration),
- finance needed for both initial installation and development of treatment as well as ongoing testing and maintenance of equipment.

In addition to the manufacturers themselves, there is information on the technologies available from the World Health Organisation on how to select the most appropriate technology for the prevailing conditions.

7 THE HISTORY AND FURTHER EMERGING PROBLEMS OF PHARMACEUTICAL AND PERSONAL CARE PRODUCTS (PPCPs)

The World Health Organisation estimates that around 3% of waste from Primary Care Treatment Centres comprises pharmaceutical products and chemicals [5].

“Pharmaceutical waste” (aka PPCPs), which includes used and unused expired prescription pharmaceuticals, home-use personal care products, and over-the-counter medications, have emerged since the development of standard medical waste regulations as being a new major public and environmental health concern. Significant research has been performed worldwide and data have been collected regarding the complex issues associated with this waste stream. In the United States, the EPA has

performed multiple studies and research relating to the existence and effects of PPCPs in the environment. Links to important worldwide research, data, and literature references can be found on the EPA website [13]. In 2009 EPA began the process of regulating pharmaceuticals recognizing that most healthcare facilities were improperly disposing of these materials. Further proposed regulations were introduced in 2015 specific to the management of hazardous waste pharmaceuticals. As of this publication these regulations have not been released but are due to be released in 2018. In some cases states have determined to regulate both hazardous and non-hazardous drugs under their own regulations in order to ensure proper disposal while the federal regulations are being developed. However, household wastes pharmaceuticals do not fall under these regulations.

Additionally, pharmaceuticals which fall under a special segment called controlled substances regulated by the Drug Enforcement Administration (DEA) have become an increasing concern. Other than the potential environmental impact of the drugs themselves, controlled substances have the potential to be abused or diverted for illicit use. This has become a growing problem in the US population that has led to the promulgation of regulations in 2014 under Disposal of Controlled Substances regulation. These regulations aim to ensure proper management of controlled substances that are in the inventory of healthcare facilities as well as those that have been dispensed to patients (household generated wastes).

8 CONCLUSIONS AND FUTURE CONSIDERATIONS

Currently established frameworks and standards relating to the characterization, packaging, treatment, and disposal of RMW/HCW from an international perspective demonstrate a range of disparities according to cited

literature and are generally dependent upon several factors:

- existing socioeconomic issues and government provisions (or lack thereof) available for the appropriate segregation and treatment of this potentially hazardous waste stream,
- the level and quality of education and resources provided to the clinicians and the public,
- the provision and use of appropriate treatment technologies capable of affording the most viable and effective disposition of these waste streams,
- regulatory initiatives and enforcement provisions available to curtail the inappropriate handling, treatment, and disposal of items within this waste stream,
- difference in regulatory requirements between commercially generated waste streams versus home generated wastes.

Many industrialized nations have developed regulations which adequately and effectively provide for safe and environmentally viable means for the treatment and disposal of RMW/HCW, but financial and regulatory burdens remain significant obstacles for nations lacking necessary resources.

Other emerging environmental concerns originating from the evolution, production, and provision of new and existing drug treatments (pharmaceuticals) in the healthcare industry may also prove to require urgent and immediate attention and response by environmental regulatory agencies. Although substantial progress has been made by some countries regarding the proper segregation and disposal of pharmaceutical compounds, the disposal of unused, used, and expired pharmaceuticals and other personal care products is still largely unregulated in other countries.

RMW/HWC management will need to continue to be a focus of international regulatory agencies and society overall as new and more

dangerous infectious agents emerge. As seen during the 2014 Ebola outbreak, there was much concern about the potential international implications of the spread of disease. International communities working together will help to provide consistency in the proper management of RMW/HCW wastes and help to reduce the risks associated with these wastes into the future.

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Further Reading

Agricultural Waste and Pollution

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1 INTRODUCTION

Although a few remaining hunter-gather peoples live without the need for true agriculture, for most of the world's population farming in its many forms is vital in order to produce the food and other crop- and animal-derived products that are necessary for today's modern lifestyles. The breeding and domestication of plants and animals to increase production was a key driver for the development of the earliest civilizations and continues to be our best hope for supplying the food needs of people around the globe. Consequently, agriculture covers a significant part of the earth's land surface (around 37% overall, see Fig. 28.1), is a major user of resources (e.g., water: accounting for approximately 70% of all global abstractions [1]), and has the potential to lead to a wide range of negative environmental

impacts. Nevertheless, it is a highly varied sector, which often includes a large number of small businesses, utilizing a wide range of systems to produce a bewildering array of plant- and animal-derived products, each of which faces its own mix of waste and pollution management challenges. This mix is also spatially variable, with different farm types, business sizes, and intensities of production in different locations. Just within the United Kingdom, for example, grazing livestock tend to be concentrated toward the north and west of the country, while field scale arable and horticultural production is located more toward the south and east.

Since the Second World War, there has been a significant change in the way in which the industry has operated, particularly (but not exclusively) in the developed world. This has involved an explosion in the use of inorganic fertilizers (Fig. 28.2),

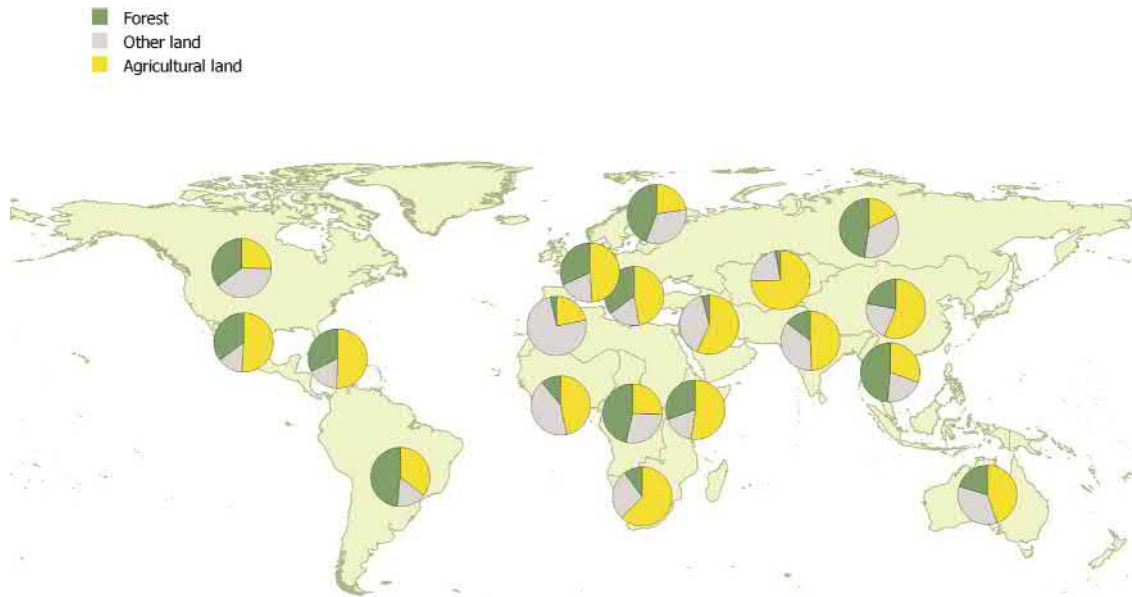


FIG. 28.1 Proportion of agricultural land in different regions of the world [2].

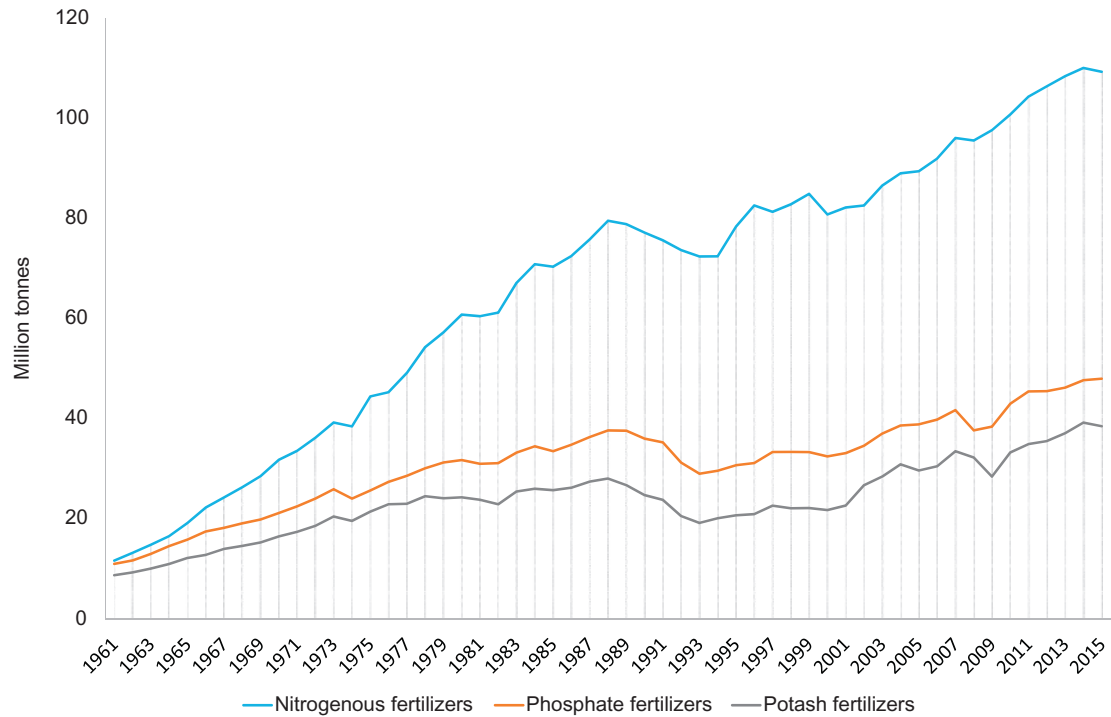


FIG. 28.2 Agricultural use of fertilizers [2].

including nitrogen-based fertilizers such as ammonium nitrate and urea derived from industrially produced ammonia (e.g., through the Haber-Bosch process), and phosphorous and potassium fertilizers from mineral sources. Simultaneously, the industry's use of crop protection products (pesticides) and levels of mechanization have increased, reliance on manual labor reduced, and our ability to utilize bioengineering has resulted in a step change in the rate at which new and amended traits can be introduced into agricultural plants and animals. Such intensification has led to marked increases in the productivity of the agricultural sector (see Figs. 28.3 and 28.4) and has played a key role in reducing levels of extreme poverty, albeit on a global scale there is still a long way to go. This has not come without an environmental cost however, with many examples of increased waste

generation, pollution, damage to ecosystems, and impaired functioning of ecosystem services, for example. In addition, very intensive forms of agriculture are viewed with suspicion in many parts of the developed world, where environmental and animal welfare concerns are high on the political agenda. Despite this however, there is a clear need to increase agricultural production around the world, in order to address a number of major environmental and social pressures, in particular poverty, a growing world population and climate change. The world's population is already in excess of 7.3 billion, of which nearly 800 million (over 10% of the world's population) are estimated to be undernourished, and although the situation seems to be improving a little, it is clear that a large number are still struggling to meet their food needs [3]. With the world's population expected to rise to almost 10 billion by

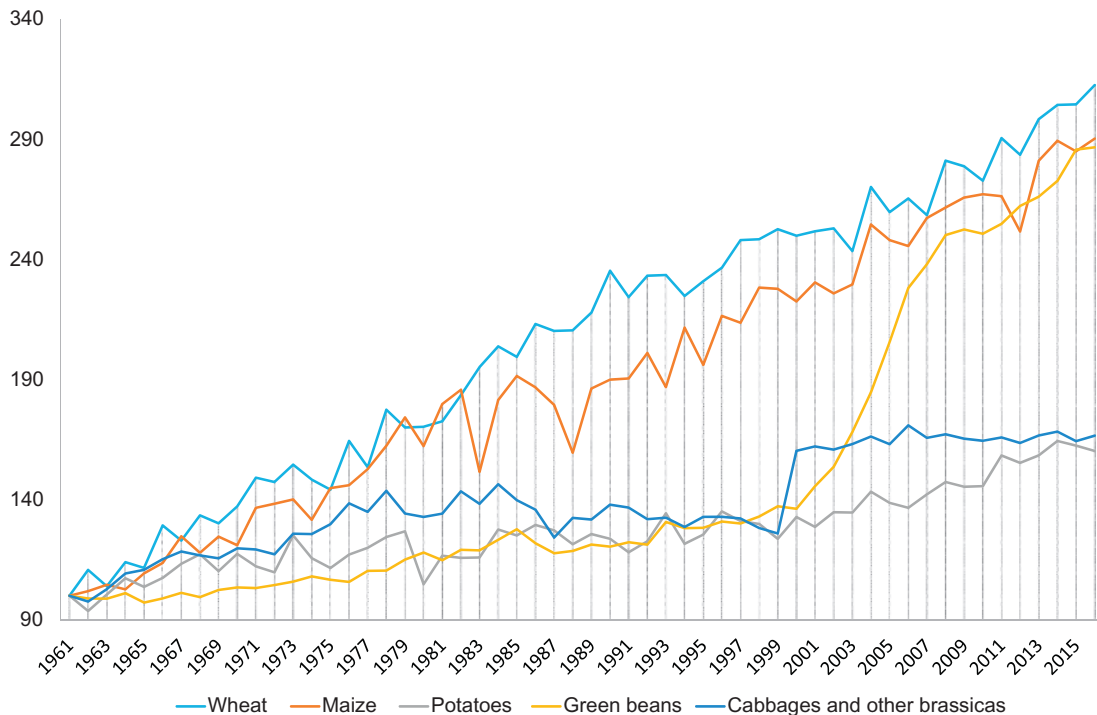


FIG. 28.3 Index of global productivity (1961=100, based on yield per ha) for sample arable and horticultural crops [2].

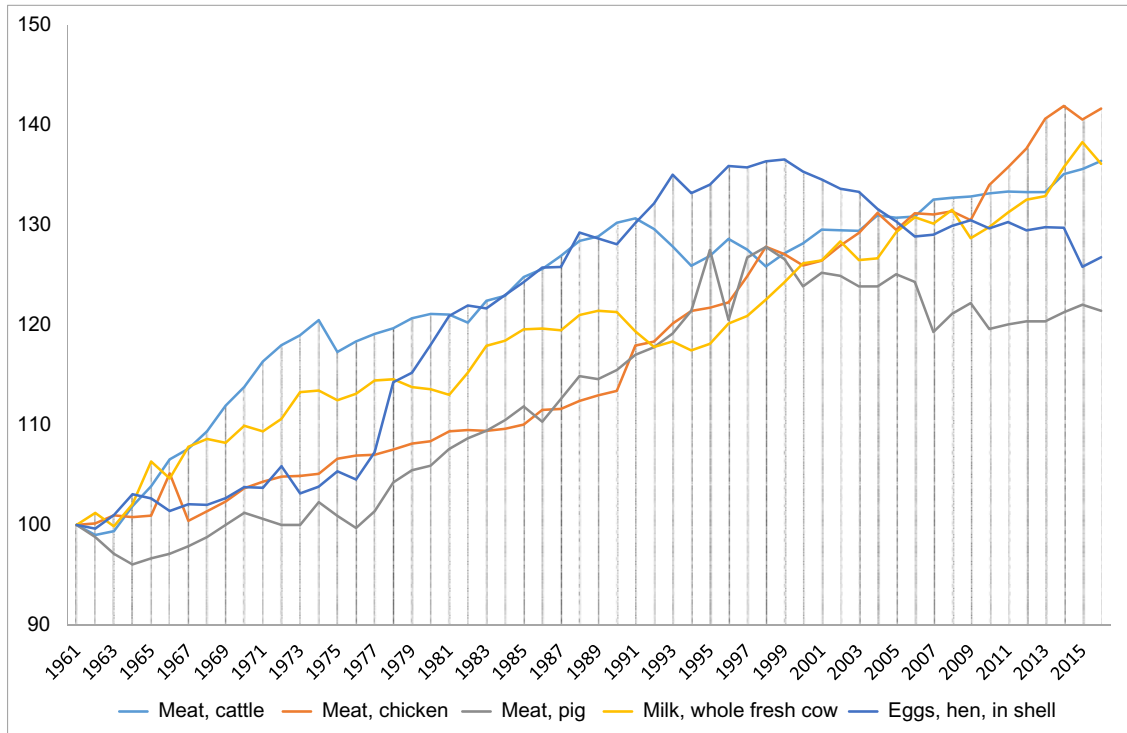


FIG. 28.4 Index of global productivity (1961 = 100, based on carcass weight for meat, yield per animal for milk and eggs) for sample livestock products [2].

2050 and 11 billion by 2100 (medium variant estimates) [4], pressure on food supplies is only going to increase; something which is likely to be exacerbated by the fact that much of the forecast increase in population is likely to be in the world's less developed countries [5]. Should poverty be reduced however, and this is certainly a key objective, it could have a considerable impact on the sort of foods demanded from the industry. Increasing wealth has often been associated with an increase in demand for foods that can, either directly or indirectly, be associated with increased waste and other environmental contamination, including meat [6] and higher value fruit and vegetable crops.

Clearly then this places a great onus on agriculture in all its forms to step up production, so

as to ensure that the population has access to sufficient, safe, and nutritious food [7] at an affordable price. Indeed, as a combined result of the above changes, the Food and Agricultural Organization of the United Nations (FAO) predicts that global food production will need to increase by more than 63% by 2050 (compared to that in the 2005/2007 period), and in sub-Saharan Africa and south Asia the increase may need to be around 132% [8]. In some cases however, this will be made more difficult by the expected impacts of climate change. There is now ample evidence that surface temperatures have been increasing for a number of decades [9], and they are forecast to continue doing so, such that by the end of the century they are expected to be between 1°C and 3.7°C (mean estimates for a range of potential scenarios)

higher than in the 1986–2005 period [10]. In addition, extreme weather events are likely to be more prevalent, with heat waves, for example, lasting longer and occurring more frequently [10]. Some areas (most notably many mid-latitude and subtropical dry regions) are also forecast to see a reduction in precipitation [10], further limiting the ability of those areas to support productive agricultural systems. In contrast, there is likely to be an increase in precipitation at higher latitudes [11], possibly increasing their suitability for farming, and placing increased pressure on them to make up any shortfall resulting from reductions in productivity elsewhere. However, if this is to be achieved, it needs to be in as sustainable a way as possible, if we are to avoid excessive environmental damage. The concept of sustainable intensification (first coined in the 1990s, e.g., [12]), has therefore

garnered considerable attention over the past couple of decades, referring to a system in which food supply is increased without the negative environmental implications that have all too often been associated with intensification in the past [6, 13, 14]. Indeed some authors have argued that it should refer to a system in which the delivery of a whole range of ecosystem services is enhanced, while still increasing food supplies (i.e., one that goes beyond the mere avoidance of environmental damage) [6, 14].

One element within the drive for sustainable intensification is clearly the need to manage the waste products of the industry in all their forms, which despite often being a relatively minor component of a nation's waste production (see Fig. 28.5), results in some significant issues. Agricultural wastes are as diverse as the industry that creates them, and include a wide range

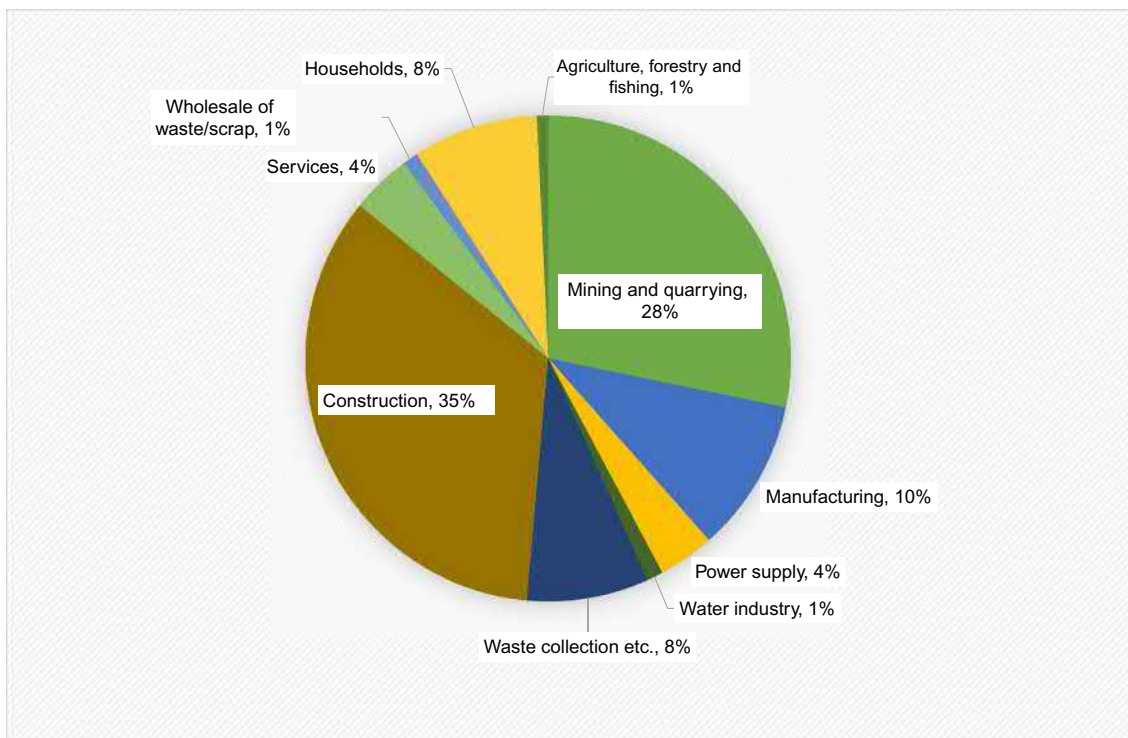


FIG. 28.5 Waste generation by economic activities and households in the EU-28 in 2014 [15].

of natural and man-made substances, including manures and slurries, crop residues, vegetative trimmings and other green wastes, pesticides, dead stock, silage effluent and wastes from the dairy industry, as well as more familiar forms of waste such as oils, plastics, paper, and card, to name but a few. Indeed, since under EU legislation, waste refers to “any substance or object which the holder discards or intends or is required to discard” [16], almost anything used and/or produced in the process of farming could become waste under certain circumstances, and consequently providing an exhaustive list is neither practical nor desirable. However, according to the OECD, agricultural waste is [17]:

... waste produced as a result of various agricultural operations. It includes manure and other wastes

from farms, poultry houses and slaughterhouses; harvest waste; fertilizer run-off from fields; pesticides that enter into water, air or soils; and salt and silt drained from fields.

Consequently, this definition includes many things that might equally be considered pollution, and ignores many man-made materials and substances which would be considered as wastes by most people’s definition. It also has to be recognized that many farms have diversified into other sectors, either related or unrelated to their core business, and these enterprises also produce a wide range of wastes. Equally, incidents of fly-tipping (the illegal dumping of waste on land) are on the rise, and in the United Kingdom (e.g.), land owners/managers are normally responsible for the disposal of any wastes dumped on their land at their own expense, with wastes generally having

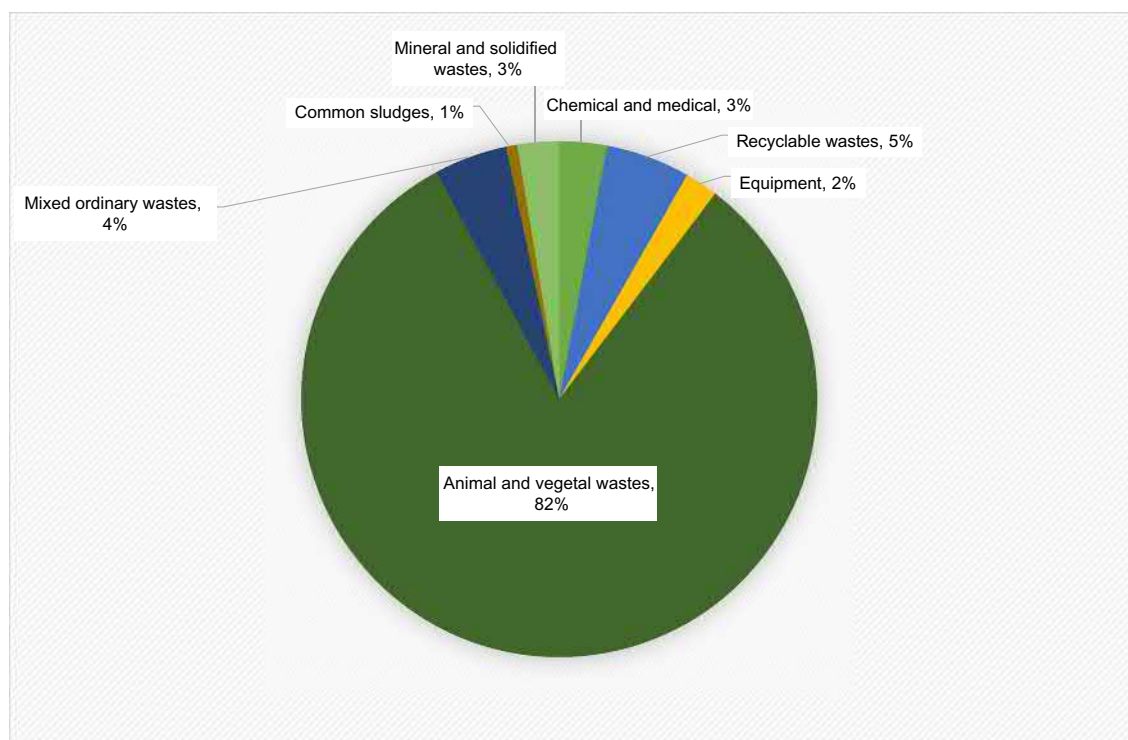


FIG. 28.6 Waste types generated by the agriculture, forestry and fishing sectors in the EU-28 in 2014 [15].

to be treated as if they were generated by the farm business. Suitable routes of disposal may therefore involve farmers having to pay their Local Authority or a registered waste carrier to remove and dispose of waste on their behalf, although it may also be possible for them to remove it themselves and transport it to a recycling center or landfill site, although a fee is often charged for this service as well [18, 19]. Nevertheless, as these wastes are generated by non-agricultural processes and could take almost any form, they are not considered further here. That waste which is farm generated, however, comes in a number of different forms, with arable farms generally producing crop wastes, agrochemicals and their containers, as well as oils, tires, and batteries from the use of farm machinery [20]. In contrast, waste from livestock enterprises tends to be in the form of animal health products and their containers, fallen stock, plastics from silage production, as well as manures, slurries, and other organic wastes (see Fig. 28.6) [20]. In both cases, however, wastes can be broadly classified as either natural or man-made, and it is this differentiation that forms the basis of the remainder of this chapter.

2 NATURAL WASTES

Until recently, it has been the natural, organic wastes produced by farm businesses that have been the focus of the majority of the research, and many of the knowledge transfer activities, undertaken in the sector. Such materials are the inevitable by-products of both arable and livestock production systems, but may be considered wastes and/or input resources depending on the site and business specific factors at play. Arable production, for example, often results in organic wastes being produced in the form of crop wastes, such as stubbles and other vegetative material left in the field after harvesting, or trimmed from crops as part of initial cleaning and processing. Such material,

however, is often reincorporated into the land to serve as a source of nutrients and organic matter, and as such is rarely considered to be a waste *per se*. In modern production systems, however, there are also significant quantities of crop which, for a number of reasons, may remain unharvested, and are therefore effectively “wasted,” together with the resources that went into their production. In the United Kingdom, for example, it has been reported that, in addition to losses that may result from poor weather, pests, and diseases, the exacting quality standards imposed by supermarkets and other major buyers can lead to up to 40% of the edible yield of some crops being rejected. When this happens, and where an alternative buyer cannot be found (e.g., for use in the production of processed foods) or contracts prevent an alternative buyer being found, this crop may either be reduced to use as animal feed or simply plowed back into the land [21]. The extent to which this can be described as waste material is of course debatable, although it is certainly waste when it comes to resources and, given that much of this food is perfectly edible, it is a significant threat to food security.

It is livestock farming however, which results in the most organic waste, since all systems produce significant quantities of manures and/or slurries. Indeed with 80Mt (80 million tonnes) of manure and slurry a year being produced in the United Kingdom alone [22], such wastes can often constitute the majority of the waste produced by the agricultural sector. In some cases this is directly deposited within agricultural fields, allowing the nutrients it contains to be recycled into the soil, but in those production systems in which animals are housed for some or all of the year, this material is collected in either solid (manure) or liquid (slurry) form, for subsequent disposal. This material, however, is generally used to benefit agricultural production, by spreading it on either arable or grassland fields to serve as a fertilizer and soil conditioner, and in so doing it plays a key role

in maintaining the nutrient status of the soil, enhancing levels of organic matter and improving structure. As a result therefore, such substances are not generally considered to be a waste, but with the increasing specialization and intensification of livestock enterprises, production of manures and slurries can often exceed the amount required by the soil for maintaining fertility, such that they may become more of a problem to be disposed of than a valuable resource to be utilized. As a consequence, there is the potential for considerable environmental damage through both their storage and disposal, and such substances therefore require effective management so as to minimize those risks.

In part, the environmental risks are associated with the potential for surface waters to be contaminated with microbiological pathogens (e.g., fecal coliforms, fecal streptococci, *Cryptosporidium* and *Giardia*, etc.) which pose a health risk to those animals and people either drinking the water (although in developed nations treatment should minimize the risk to people) or entering the water for recreational or other purposes. This is particularly likely to be the case where fecal material is either deposited directly into watercourses, either by the animals themselves, as a result of runoff of surface applied material, or through the accidental or deliberate discharge of slurry, as the time available for microbial death will be significantly lower than where manures/slurries remain on or in the soil. In addition, however, such materials exert a considerable biochemical oxygen demand (BOD), such that dissolved oxygen levels in the water column and/or bed sediments can be reduced to the point at which it can have a severe impact on aquatic biodiversity, particularly if significant quantities of material enter the watercourse over a short period of time (e.g., when a slurry store leaks or collapses), or where levels of dilution are minimal (e.g., in small watercourses and in periods of low flow).

As far as water quality is concerned, however, it is the nutrient content of manures and slurries

which is of particular concern in many parts of the world, including Europe. As mentioned before, such materials can serve as a valuable source of nutrients for maintaining the productivity of agricultural soils, but it is precisely this property which means that without careful management they can also result in significant nutrient enrichment of surface and groundwaters. For example, the addition of nitrogen to the soil in both manure/slurry and inorganic fertilizer form often results in a significant increase in the presence of ammonium (NH_4^+), which in turn can be converted into nitrate (NO_3^-) through the process of nitrification (microbial conversion). Nitrate compounds are highly soluble, which means that it is readily taken up by growing plants, and also that there is a considerable risk of leaching (movement along with soil water), and therefore the contamination of neighboring surface and groundwaters. The risk of leaching is especially high in wet conditions, when nitrogen has been added to the soil at a rate higher than can be utilized by the crop and/or when the timing of that application is such that the crop is not growing sufficiently vigorously to take up all the nitrate as it is produced (e.g., too late or early in the growing season). Phosphorus too can be lost to the environment if applied in excessive amounts, although in this case it is more likely to be when fine sediments are eroded from the field than through leaching, as this particular nutrient is generally found bound to those sediments rather than in solution. Both these nutrients therefore have the potential to upset the balance of aquatic ecosystems, by resulting in an explosion in the rate of algal and plant growth, choking surface waters, and greatly reducing their dissolved oxygen content (eutrophication). In addition, nitrogen has direct health implications, due to its potential role in methemoglobinemia (blue baby syndrome – a reduction in the oxygen carrying capacity of blood) and gastric cancers. Despite these problems, however, the use of manures/slurries

(and in many cases inorganic fertilizers) is an essential part of the productive system and key in maintaining fertility. However, where organic wastes are seen as a problem to be disposed of and their rate of application is excessive and/or applications of inorganic fertilizer fail to take full account of the nutrients supplied in organic form, there is the potential for considerable environmental damage. It is for this reason that many countries have introduced controls on and/or guidelines for the use of manures, slurries, and fertilizers. In Europe, for example, the Nitrates Directive [23] (now an important part of the Water Framework Directive [24]) required the establishment of Nitrate Vulnerable Zones (NVZs), areas in which land drains into waters polluted with, or at risk of being polluted with, nitrogen. Within these zones (unless a Member State has decided to consider the whole of its territory as an NVZ – as Germany and a number of others have), the amount and timing of nitrogen applications is controlled, with the aim of minimizing the risk to the environment, and farmers are legally required to comply with regulations. In a similar vein, the Nitrates Directive also requires Member States to establish voluntary codes of practice that are applicable to all agricultural land, regardless of their NVZ status, in order to provide a degree of protection for all waters [23]. Equally, a number of Member States have developed decision support systems in order to assist farmers in applying nutrients in such a way as to minimize the environmental risks and maximize the efficiency of their use, and which may relate either to a single nutrient (e.g., AzoFert in France – nitrogen [25]) or multiple nutrients (e.g., RB209 in England and Wales – nitrogen, phosphorus, potassium, etc. [26]).

Organic manures/slurries also have implications for the release of a number of polluting gases, including ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O). Agricultural ammonia emissions are mainly released through the breakdown of urea in the manures and slurries

of livestock [27, 28] and can be a particular problem for intensive pig, poultry, and dairy units, from which significant quantities of gas can be released from a concentrated area, creating issues for neighboring properties. In the EU, agriculture is responsible for 94% of ammonia emissions, of which 75% comes from the livestock sector, a significant proportion of which is as a result of the way in which organic manures/slurries are managed. Once it enters the environment, ammonia can be deposited in gaseous form, but is also a highly soluble gas, and within the atmosphere reacts to form a number of ammonium compounds which are deposited in rainfall [27]. In either case, the nitrogen within the deposited material enriches the environment, favoring plant species particularly capable of exploiting nitrogen-rich conditions (e.g., grasses) to the detriment of those evolved to live in more N-limited areas, damaging sensitive habitats [27]. In addition, the breakdown of manures/slurries, either in storage or after application to land, can result in the emission of methane and nitrous oxide. The bulk of methane results from enteric fermentation, but it is also emitted during the management of manures and slurries, while nitrous oxide is mainly emitted when such substances (as well as inorganic fertilizers) are added to soils. These gases have global warming potentials (over 100 years) that are 28 and 265 times that of carbon dioxide, respectively [10], meaning that agriculture is a significant contributor to overall greenhouse gas (GHG) emissions. The European Commission, for example, estimates that around 10% of the regions emissions (based on CO_2 equivalents) are from the agricultural sector, albeit that not all of this results from the management and use of organic wastes.

While spreading to land is the most common form of disposal of manures and slurries, other systems are in use. Anaerobic digestion (AD), for example, can be used to treat excess slurry (in particular), as well as other organic wastes including manures, crop residues, imported

food wastes, and so on [29]. These systems allow the production of biogas either for direct use (e.g., in farm boilers) or use in generating electricity for use on farm or for feeding into wider distribution networks [30]. In addition, however, they also help reduce GHG emissions, and result in a digestate that can still be spread on land as a fertilizer, but with significant advantages over undigested slurry (e.g., reduced likelihood of nitrogen leaching, faster regrowth, etc. [30]). Nevertheless, while AD has been shown to be an effective means of treating slurries, capturing biogas and generating heat/electricity, capital costs, and planning constraints are often seen as significant barriers to uptake [30]. Similarly there is much focus on making the most of crop wastes, which as well as using them to improve soil fertility and structure, or in AD systems, may mean using them to produce biofuels (e.g., ethanol, methanol, biodiesel, etc.) or (along with crops grown specifically for the purpose) in small scale heating, or indeed in combined heat and power systems, reducing the need for fossil fuel consumption, and therefore GHG emissions.

Animal-based agriculture also results in a number of other natural substances which may genuinely be classified as wastes. In particular, those categorized as “animal by-products” (ABPs), most notably in the form of fallen (dead) livestock, require careful handling and disposal, since such materials have the potential to be a significant threat to both human and animal health. Indeed, the importance of their correct disposal has been brought into sharp focus through the problems associated with bovine spongiform encephalopathy, for example. In the EU, Regulation (EC) 1069/2009 and Regulation (EC) 142/2011 that implements it [31] require farmers to collect, identify, and transport carcasses from their premises as soon as practical, although some short-term storage in bins is permitted. Burning or burial on-site, which used to be the norm, is no longer permitted, except in a limited number of circumstances, with carcasses instead being transferred to one of a

number of approved businesses for disposal through processes including rendering and incineration, some of which result in a variety of useful products, such as hides for leather, pet food ingredients, biodiesel, and biofuels. Such measures are intended to reduce the likelihood of the spread of disease, either through potentially contaminated materials entering the human or animal food chain, or through contamination of soils, water, or the atmosphere [32]. In the dairy industry, an additional risk is posed by waste milk, since this material has a very high BOD (approximately 120 g L^{-1} for fresh milk [33], which is around double that of silage effluent and six times that of cattle slurry), such that it has the potential to have a very significant impact should it escape into the aquatic environment. In the main of course, milk is a product not a waste, but nevertheless, there are occasions when some is in need of appropriate disposal, including that produced by cattle treated with certain veterinary products, left-over milk from pipes and storage systems, and indeed full loads that for whatever reason (e.g., bad weather) cannot be collected in due time [34]. As a by-product of animal production, milk can be covered by the same legislation as other such by-products, although where disposal is on the farm on which the milk was produced, this generally is not the case, and the regulations are far less restrictive. Some waste milk can therefore be used as a livestock feedstock [35], with the remainder often being spread on land [36] (with some restrictions, i.e., if livestock have been administered certain substances), although other forms of disposal (such as AD) may also be used. Where farmers wish to spread milk on land, however, there may still be some restrictions on their ability to do so, as in England, for example, farmers wishing to spread milk first require a waste disposal permit from the Environment Agency, or need to be in possession of an exemption from them [36]. The latter of which restricts the amount that can be applied, the frequency of those applications, and also

requires applications to be kept away from watercourses and springs, and that milk should first be diluted with water or slurry [37].

2.1 Organic Wastes Brought Onto the Farm

As well as farming's role in producing and managing agricultural wastes, the industry also has a role to play in managing organic wastes from other sectors, particularly where other options for disposal have diminished. Within the European Union, for example, the Landfill Directive of 1999 (1999/31/EC) set the target of reducing the amount of biodegradable municipal waste going to landfill by 25%, 50%, and 65% from 1995 levels by 2010, 2013, and 2020, respectively [38], leading to an urgent need for alternative disposal routes. It is a similar story when it comes to the disposal of sewage sludge, with the Urban Waste Water Treatment Directive [39] banning the disposal of this material in surface waters (including the sea) in the EU, from the end of 1998 (Article 14), so that again there was need to find alternative methods of disposal. Among the alternatives available is application to agricultural land, where much like farm produced organic wastes, such materials serve as fertilizers and soil conditioners, and therefore have the potential to be a valuable resource for the industry. Nevertheless, the application of such wastes to productive land is not without its problems, due to the possibility of contamination of the soil (e.g., heavy metals in sewage sludge) and crops (e.g., microbiological contaminants) as well as issues associated with odors [22]. Consequently, the regulations affecting the spreading of nonagricultural wastes on land tend to be tighter than those for organic wastes produced through farming activities, in order to protect public health and the environment. For example, in relation to sewage sludge, EU [40] and domestic legislation (e.g., [41]) sets limits on the levels of heavy metals that can be present in soils, sludge, and the average amount

that can be applied each year, as well as the time which must elapse before certain crops can be harvested from treated land or livestock permitted to graze on it.

3 MAN-MADE WASTES

Although many of the previous natural wastes can be considered as resources, modern farming also results in many waste streams involving man-made materials that can only be considered wastes, albeit that they account for a minority of those produced by the industry (see Fig. 28.6 for EU data). Many of these man-made waste streams will be familiar to those with experience of waste management in other sectors, including construction wastes, machinery-based wastes (i.e., oils, batteries, tires, and used machinery itself), for example [22]. Such wastes can often be treated in much the same way as those produced in those other sectors, and managed according to the waste hierarchy (see Fig. 28.7), something which is now enshrined in European legislation [16]. Nevertheless, the nature of agricultural businesses means that some cannot simply be treated in the same way as those generated in, for example, the domestic sector. This is due, in part, to the expected levels of contamination.

Packaging, for instance, has been a major waste management issue in many sectors for a number of years now, and the agricultural sector is no different. In the United Kingdom, for example, an estimate of agricultural waste production in the late 1990s suggested that the country's farming industry was producing just over 44,000 t year⁻¹ of packaging waste of one sort or another [22]. The bulk of this ($\approx 73\%$ – see Fig. 28.8) was in the form of plastics (e.g., polyethylene and polypropylene), particularly the bags used in the supply of fertilizers and livestock feeds, with another 23% being paper and cardboard [22]. Many of these forms of waste can be treated like packaging from other sectors and

FIG. 28.7 Waste management hierarchy in descending order of desirability [16].

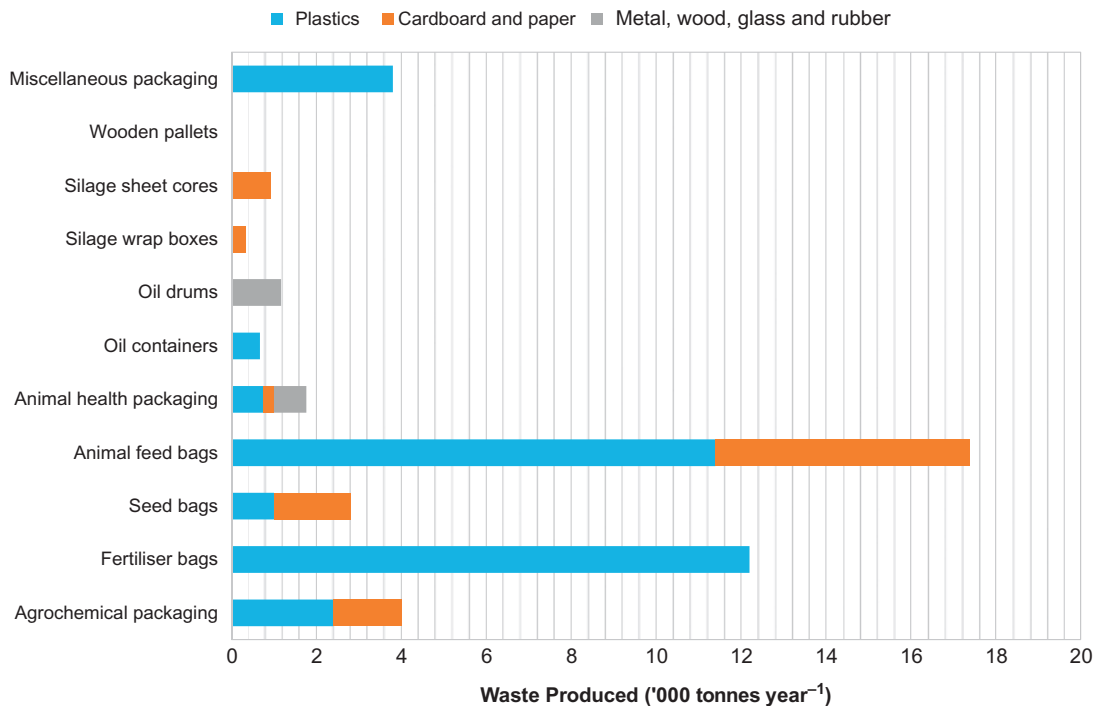
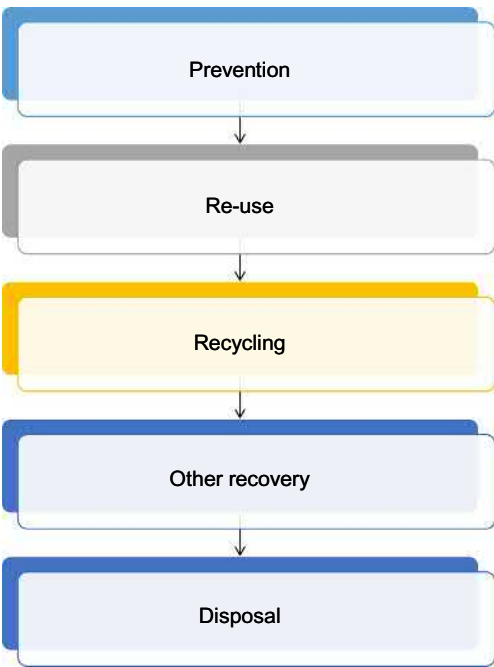


FIG. 28.8 Estimated packaging wastes produced by the UK agricultural sector [22].

managed on the farm according to the general waste hierarchy. For example, where purchases of packaged materials are being made, this can be done in such a way as to minimize that packaging, by using fewer but larger containers, water soluble bags, or containers designed to be returned to the supplier for reuse. Some packaging, however, can be associated with significant environmental and health risks that mean that considerably more care is required in its management. In particular, it is important that those containers associated with agrochemicals, veterinary medicines/treatments, and fuel oils are not reused for other purposes [22], due to the risk of contaminating any new contents with harmful chemicals. In the EU, most Member States suggest that pesticide containers should be rinsed three times (inside and out), and the washings added to the sprayer, so that the containers can subsequently be considered nonhazardous [42]. Some product labels will, however,

prohibit this [43], for example, where water might react with the chemical contents to produce toxic gasses [43]. Either way, unless containers have been specifically designed to be returned to the supplier, refilled and reused (again in line with the aims of the waste treatment hierarchy), there is a clear need to ensure that they are disposed of in such a way as to pose no wider threat. United Kingdom guidance, for example, requires that a licensed waste contractor or site be used [43], rather than mixing pesticide containers in with other waste produced on the farm, such as that from domestic residences.

As well as for packaging, modern agricultural and horticultural businesses use plastics in a number of other forms, including plastic piping, twine, tree-wraps, pots, seedling trays, and so on (see Fig. 28.9). Indeed it is these forms which may make up the majority of the plastic waste generated by a farm enterprise, with the EU, for example, producing 1.326 Mt. of nonpackaging plastic

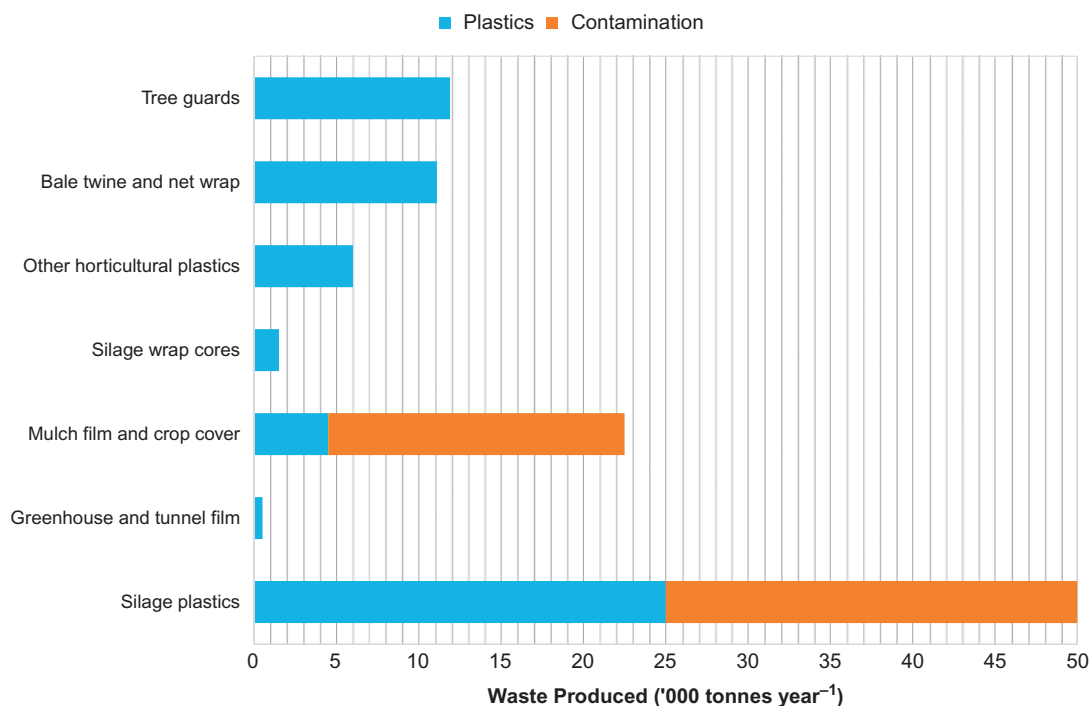


FIG. 28.9 Estimated nonpackaging plastic wastes produced by the United Kingdom agricultural sector [22].

waste in 2014 [44]. Horticulture often uses plastic films to act as a mulch (e.g., when growing potatoes), so as to reduce evaporation, maintain soil water levels, warm plant roots, and reduce weed establishment (and therefore the need for pesticides) [22, 44]. It can also help reduce contact between the above ground parts of plants and the soil, reducing contamination and therefore the need for washing, which can be useful in relation to salad crops. Similarly plastics are used to provide various forms of crop cover, ranging from sheets of plastic over some vegetable crops to a whole range of polytunnels of varying sizes (Fig. 28.10). This latter form is (again) particularly used in horticulture, where polytunnels perform many of the same functions as traditional glass-houses (greenhouses). In 2015 just over 36% of the EU area given over to the production of fresh vegetables was located in just two countries (Italy: 19.5% and Spain: 16.6%), where a significant proportion of the crop was grown under plastic (in the main, although glass is also used) to control humidity (Spain: 17.2%, Italy: 13.3) [46]. It is no surprise therefore, that these two countries are among the largest producers of waste agricultural plastics in Europe [44]. Polytunnels are also used in livestock agriculture, where they are used to provide livestock cover/housing, but in this sector the most important sources of plastic wastes are those associated

with the production of silage. Silage is made through the fermentation of cut grass under acidic conditions, which is generally carried out either in mounds covered with weighted down plastic sheeting (silage clamps) or in large bales wrapped in plastic (Fig. 28.11). Both forms of production have increased considerably in recent decades, as a means of increasing the nutrient content and palatability of preserved fodder, and as result considerable quantities of waste are produced, particularly in the dairy and beef sectors, such that countries in which there is a significant livestock industry produce large quantities of this film/sheet plastic waste. In the Republic of Ireland, for example, silage wrap was responsible for 87% (16.487kt) of all farm plastics sold in 2016 [47]. Wastes consisting of silage wrap/film and/or horticultural plastics (particularly mulch films) can be contaminated with significant quantities of soil, silage, and vegetative material, significantly increasing the weight that must be managed (Fig. 28.9), and potentially decreasing the options for that management. Nevertheless, both forms of plastic are generally composed of a single material, in principal at least making them suitable for recycling, and a number of such schemes have been introduced in recent years (see Section 4), although at present only 28% of agricultural plastics are recycled in the EU, with 42% going to

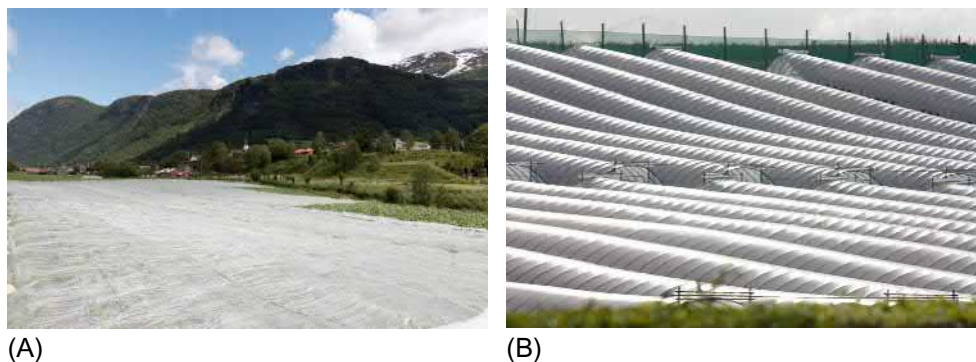


FIG. 28.10 Crops being grown under (A) plastic sheets in the Vik valley (Norway), and (B) plastic polytunnels in Fife (Scotland) [45].



FIG. 28.11 Silage bales wrapped in plastic [45].

landfill and 30% to energy recovery facilities [44]. An alternative is the use of either genuinely biodegradable plastics or so-called oxo-plastics which contain an additive designed to make them become brittle and breakdown. However, the performance of the former is limited at present, while the latter have been associated with environmental damage (e.g., the contamination of soil and water with micro-plastics) in their own right [44].

Many farming systems make considerable use of a wide variety of agro-chemicals, including both pesticides (e.g., insecticides, herbicides, fungicides, etc.) and livestock veterinary products, in order to increase yields and/or protect product quality. Indeed such chemicals have played a central role in driving forward the productivity of the industry [48], and if we are to meet the food security challenges of the future, they are likely to continue doing so. The exceptions, of course, are organic production systems, although even here some chemicals are permitted either for crop protection or animal welfare reasons [49]. Pesticides are used by both arable/horticultural enterprises and in the production of grass in support of livestock businesses and may result in waste in the form of unused product, equipment washings, contaminated clothing and other materials, and

any excess applied to crops and surrounding areas (although the extent to which this can be described as waste in the conventional sense is debatable), as well as the packaging (often chemically contaminated) discussed before. Despite their undoubted usefulness, when such substances enter the wider environment, they have the potential to result in significant damage to aquatic and other nontarget habitats, biodiversity, and human health [48]. Some of these risks can be mitigated by effective management of the way in which chemicals are stored (i.e., so as to ensure that spillages cannot escape into the environment [43]) and used. In the latter case, many guidelines aimed at minimizing the environmental impact of pesticides stress the importance of reducing pesticide use to a minimum (although the recommended dose should always be used so as to reduce the likelihood of resistance developing) by making maximum use of other control strategies (e.g., crop rotations, cultural controls, biopesticides, and natural predators) and ensuring that spraying only occurs once suitable pressure thresholds have been reached [50], in what is termed a program of Integrated Pest Management (IPM – itself part of the wider approach to management known as Integrated Farm Management or IFM).

If the previous minimization approach to pesticide use is taken, then the amount of active substance being purchased and used, and therefore capable of causing environmental damage will be reduced, but it will rarely be eliminated altogether. Consequently, where potentially harmful (they are after all designed to kill something) chemicals are used, then it is likely that some will be left over and therefore need to be managed as waste. For example, there may be some concentrate remaining unused once a crop has been sprayed or when approval to use a particular chemical is withdrawn or amended. Indeed, due to the threat posed by such chemicals to the water environment, some water utilities have offered “amnesties” in certain sensitive catchments, under which they will arrange for old pesticides to be disposed of safely and free of charge (e.g., [51]). In most cases the need to manage waste concentrates can be minimized by ensuring that products are purchased in appropriately sized packages, and that whenever possible unapproved chemicals are used up within the withdrawal period; however, if this is not (for whatever reason) possible, then it is essential that such substances are appropriately managed. In some cases, for example, it may be possible to return unused product to the supplier, but if not the hazardous nature of pesticides means that the approved disposal routes are often tightly regulated. In England and Wales, for example (similar legislation exists elsewhere in the EU), the Hazardous Waste (England and Wales) Regulations 2005 require (among other things) farm businesses to store and handle hazardous waste separately to nonhazardous waste, and to use authorized (licensed) waste transport/management businesses to collect and/or dispose of that waste.

Dilute pesticide wastes, such as those often found in or on spraying equipment (as excess spray or as contamination on machinery), also need careful management, and again minimizing the production of this form of waste is key. In particular, there must be careful planning of

spray operations so as to minimize the amount left over at the end. Nevertheless, at least some excess is almost inevitable, and equipment will need to be cleaned inside and out, so in the United Kingdom, for example [43], it is recommended that this is done in the field using either untreated or treated areas of land, although in the latter case care must be taken not to exceed the recommended application rate. Where this is not possible however, dedicated filling/cleaning areas can be used, which are generally areas of hardstanding designed to capture any runoff and either direct it toward a holding system for later disposal as a hazardous waste (see earlier), or to some form of treatment such as a biobed. Biobeds are lined structures filled with a mixture of straw compost, peat-free compost, and soil (biomix) topped with turf and are used to promote the microbial degradation of contaminated runoff, accidental spillages, and equipment washings [52]. Pesticide removal rates can be as high as 95%–99% [53], although considerable variations exist due to the fact that efficacy is highly dependent on the properties of the chemicals involved [52]. As a result of this uncertainty over their effectiveness therefore, together with the relatively high costs involved in construction, real or perceived difficulties in obtaining authorizations to discharge the resulting leachate, and a lack of clarity as to the maintenance required, biobeds are currently only present on a minority of farms [52–54].

The other group of agro-chemicals of particular concern for the environment are the various forms of veterinary treatment, and although the significance of such chemicals was for a long time overlooked, the environmental issues surrounding them (and indeed other pharmaceutical products) have been receiving increasing attention in recent years. These substances have the potential for deleterious effects on human health, the environment (surface and groundwaters), and biodiversity, with increasing evidence of negative impacts on wildlife [55]. This includes a number of wastes (e.g., needles

and syringes) which might be considered hazardous, and therefore require disposal by specialists [22]. In addition, however, medicines given to livestock either internally or externally can escape into the wider environment, through (e.g.) being washed from the skin or deposited in manure and/or urine, and as far as farmed animals are concerned, those that have garnered the most interest are the *endo*- and ectoparasiticides. Ivermectin (an antiparasitic mainly used as an anthelmintic, but also in the treatment of a number of species of mites and lice), for example, has been shown to be excreted in feces and have a negative impact on invertebrates that feed on dung, and therefore the birds and small mammals that feed on them [55]. Sheep dips, used to control sheep scab (allergic dermatitis caused by the mite *Psoroptes ovis* and its feces) are also prone to environmental release due to the way in which they are used, which among other things results in the production of considerable volumes of waste dip requiring disposal. As a result these products have come in for considerable attention, with United Kingdom users now needing (currently under the Veterinary Medicines Regulations 2013) a *Certificate of Competence* to buy or use them. The risk to human health is a key driver for controlling this sort of product, with organophosphate dips having been associated with a number of chronic health effects in users; but nevertheless, there are also a number of environmental concerns surrounding both the use of dips and the management of waste dips. In Europe, for example, Article 6 of the Groundwater Directive [56] requires Member States to take “all measures necessary to prevent inputs into groundwater of any hazardous substances,” where hazardous substances are in essence those referred to in Annex VIII of the Water Framework Directive [24], which includes the organophosphates used in many sheep dips. Despite this, it has been, and in some cases still is, common practice for used dip to be disposed of by spreading on land, although in the United Kingdom at least this

requires a license from the appropriate environment agency, due to the risks posed to both surface and groundwaters [57, 58]. Such sources may only account for a small proportion of environmental pollution, but due to the nature of the chemicals involved and the way in which they are used, they have the potential to result in localized high concentrations, with perhaps dramatic consequences for aquatic biodiversity and abstraction points used for human supply. As an alternative form of waste disposal, it may be possible (depending on the product) to use appropriate detoxification chemicals to break down the active ingredient prior to land application and/or to dispose of them via a registered contractor [57, 58].

4 THE CHANGING FACE OF AGRICULTURAL WASTE MANAGEMENT IN EUROPE

Until recently, the options available for the management of wastes on farms in Europe were considerable, with a degree of flexibility that would be unfamiliar in other sectors. In the United Kingdom, for example, agriculture was for many years excluded from many of the controls imposed on other sectors, meaning that a considerable proportion of many wastes were disposed of on-farm (see Fig. 28.12). In particular, the burning of waste was common for plastics, and the burying of waste was still permitted. However, such an approach was found not to comply with the EU's Waste Framework Directive, and as a result the regulations applying to agriculture were brought into line with those of other sectors in the mid-2000s (by the Waste (Scotland) Regulations 2005, Waste Management (England and Wales) Regulations 2006 and Waste Management Regulations (Northern Ireland) 2006). Under EU law (the Revised Waste Framework Directive 2008/98/EC), Member States are required to apply a waste hierarchy for waste prevention

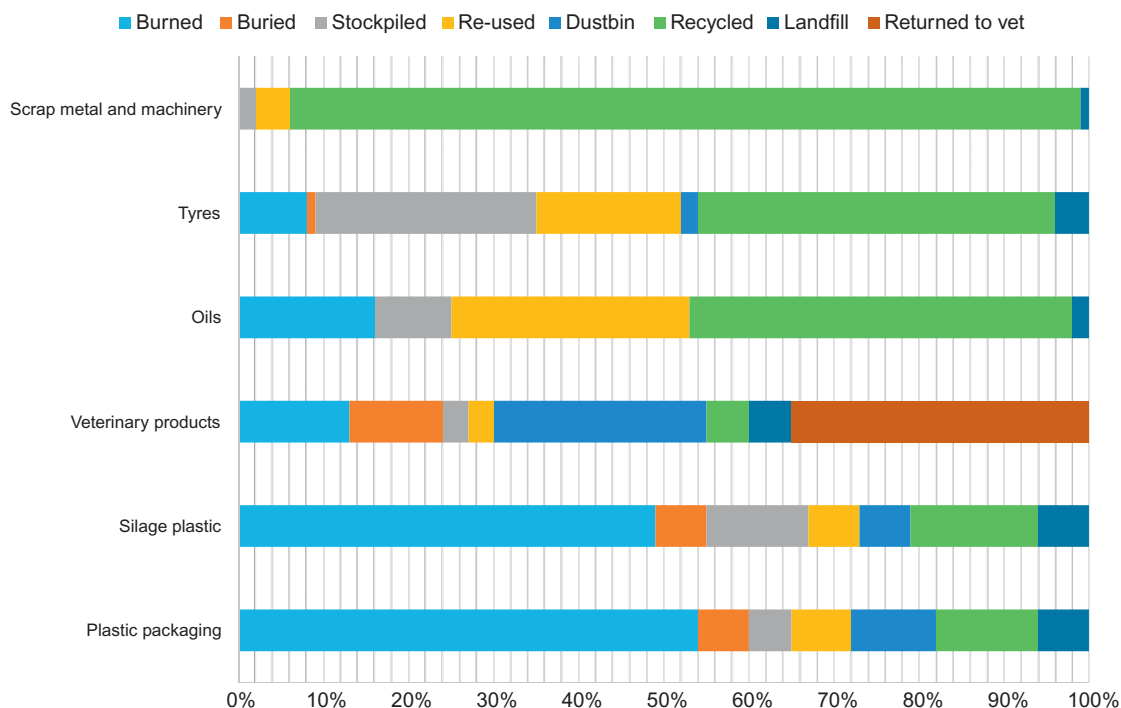


FIG. 28.12 Disposal/management of United Kingdom agricultural wastes in 2000 [22].

and management in legislation and policy (see Fig. 28.7), which had clear implications for the way in which agricultural waste should be managed, placing far more emphasis on the reuse and recycling of waste. For some wastes, reuse/recycling has always been the major form of management (e.g., organic wastes), but for others increasing legislation has seen a marked change in the way in which agricultural businesses have had to go about the process of waste management. In the main, the burning, burying, and mixing with domestic waste have been banned for many forms of agricultural waste, and the use of recycling schemes has greatly increased (see Fig. 28.13), particularly in relation to the various forms of plastics used on farms (including pesticide containers), which has in part been facilitated by the increased availability of recycling options. In the Republic of Ireland, for example, the Waste Management (Farm

Plastics) Regulations were introduced as far back as 1997 (and revised in 2001), and required companies placing agricultural films on the market to either become involved in recycling themselves (i.e., allow them to be returned for recycling) or participate in a government approved recycling scheme (i.e., the Irish Farm Film Producers Group – IFFPG). In 2016 this latter national scheme recycled 27.193 kt of plastics waste, or around 74% of the plastics its members placed on the market (allowing for 50% contamination – [47]). There are also similar schemes in existence in many other European countries, run by either the state, private companies, or industrial groups [60]. These include [44]:

- Erntekunststoffe Recycling Deutschland (ERDE): A national recovery program funded by member companies in Germany which recovered 5.412 kt of plastic film in 2016.

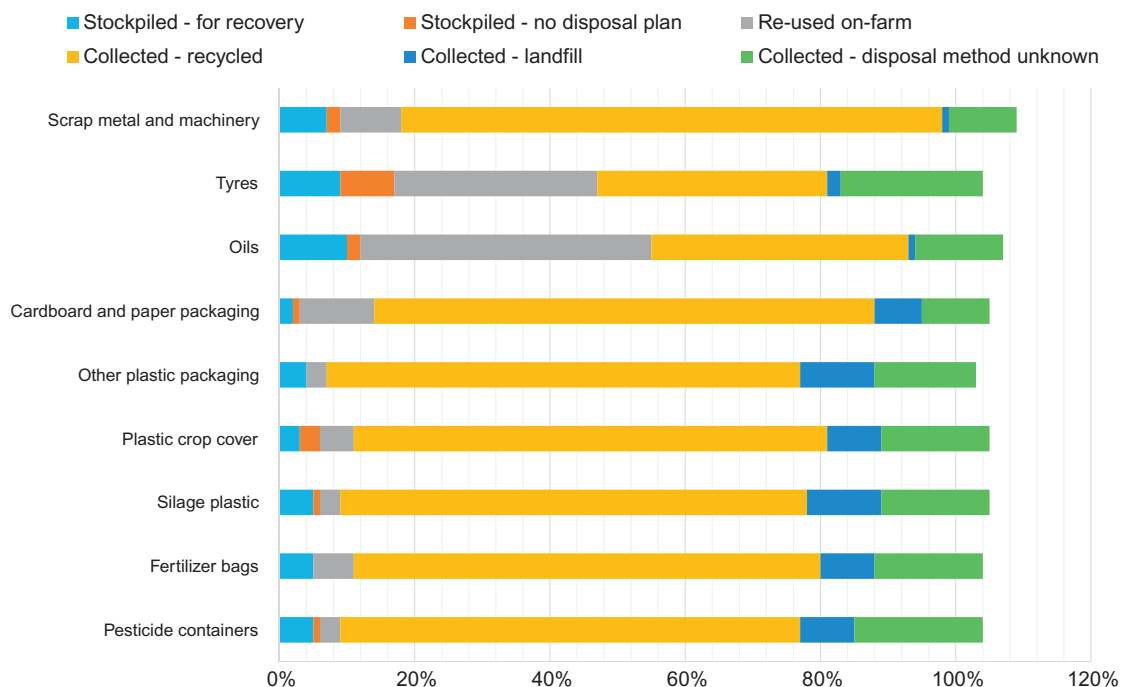


FIG. 28.13 Proportion of English farm holding utilizing specific waste disposal/management routes in 2012 (Note: individual farms may use more than one disposal route [59]).

- **Cicloagro:** A system funded through an “eco-protection” tax on the sale of agricultural plastics and authorized to collect nonpackaging agricultural plastics by the Andalusian government (under Decree 73/2012).
- **ADIVALOR (Agriculteurs Distributeurs Industriels pour la VALORisation des déchets agricoles):** A voluntary French scheme set up by manufacturers, distributors, and farmers (via the unions) under the auspices of the UIPP (French crop protection industry association), which deals with a range of packaging, plastic film and pesticide wastes.

Clearly then considerable progress has been made in recent years in dealing with the wastes generated by the agricultural sector, particularly in the developed world, but there is nevertheless still much that could be done.

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Military Solid and Hazardous Wastes: The Army Corps of Engineers Disaster Debris Management Mission

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1 INTRODUCTION

In the United States, the 1988 Stafford Disaster Relief and Emergency Assistance Act outlines the Federal government's roles in responding to large disasters. The first step is for an event to be declared by the President as

a National Disaster or Emergency. The Federal Emergency Management Agency (FEMA) is the lead agency in coordinating the Federal response, which is generally integrated with State and local governments and agencies. The United States Department of Defense is specifically assigned the role of "clearance and

removal of debris and wreckage for essential government functions during an emergency.” This debris mission is generally led by the U.S. Army Corps of Engineers (USACE). The USACE may also be assigned additional responsibilities by FEMA during a disaster response. For example, in the response following Hurricanes Irma and Maria (2018), the USACE was assigned the mission of restoring power and providing temporary roof to the island of Puerto Rico. However, the debris mission is paramount and will be the focus of this chapter.

2 BACKGROUND

2.1 Disasters

There are a wide range of disasters that could result in a FEMA response. These include, but are not limited to:

- industrial accidents, including chemical releases and explosions
- terrorist events
- landslides
- volcanic eruptions
- earthquakes
- uncontrolled wildfires
- heat waves
- tsunamis
- large river flooding
- dam failures
- extensive thunderstorm activity
- snow or ice storms
- tornadoes
- hurricanes (adapted from Perrow [1]).

Not all of these disasters result in debris missions that require USACE response, but many do. Of these, hurricanes have historically had the potential for massive debris missions. This chapter fills therefore focus on hurricane debris, however, other events could potentially generate significant debris missions as well.

2.2 Historic Debris From Hurricanes

Hurricanes can generate enormous quantities of debris on the order of years, perhaps decades, greater than the average annual solid waste levels in a given community [2]. Hurricane Andrew (1992), for example, generated $32.9 \times 10^6 \text{ m}^3$ (43 million yd^3) of debris in Metro Dade County, Florida [3]; Hurricane Iniki in Hawaii generated $3.8 \times 10^6 \text{ m}^3$ (5 million yd^3); Hurricane Hugo generated $1.5 \times 10^6 \text{ m}^3$ (2 million yd^3) of plant waste, which was on the order of 5–15 times the annual solid waste produced in both North and South Carolina [3]; Hurricane Sandy (2012) generated $7.6 \times 10^6 \text{ m}^3$ (10 million yd^3) of debris, including nearly $9 \times 10^6 \text{ kg}$ (200 million lbs) of toxic wastes in New Jersey and New York; Hurricane Harvey generated about $3.8 \times 10^6 \text{ m}^3$ (5 million yd^3) of debris, but was complicated by a toxic release to a chemical plant and damage to a hazardous waste disposal site; and Hurricane Irma generated about $3 \times 10^6 \text{ m}^3$ (4 million yd^3) of debris in Florida, including the release of more than $100 \times 10^6 \text{ L}$ (28 million US gallons) of untreated sewage throughout the state. The $90 \times 10^6 \text{ m}^3$ (118 million yd^3) of debris produced by Hurricane Katrina made it the largest debris cleanup project to date in the United States [4].

These large fluxes mean that even conventional waste streams can become severe environmental hazards due to their large volumes. Furthermore, the large volumes can overwhelm existing landfill space, particularly those for hazardous and municipal wastes.

2.3 Categorization of Debris

Debris from disasters can be categorized into the following types [5]:

- vegetative materials
- clean lumber
- inert materials
- building materials

- chromate copper arsenate (CCA)-treated wood
- putrescent wastes
- hazardous household wastes/materials (HHHW)
- others, including electronics (e-wastes), human wastes (night soil, sludge).

These debris types are discussed in detail in Channell et al. [5], including discussion of problematic materials commonly found.

3 APPLICATION OF NET ZERO PRACTICE TO DEBRIS MANAGEMENT

3.1 Net Zero Waste

The concept of Net Zero Waste (NZW) is depicted in Fig. 29.1. It focuses on diversion of the wastes, which means that it seeks to reduce wastes first and then focuses on finding useful repurposing and recycling of materials currently managed as wastes [6]. The ultimate goal of a typical NZW program is to achieve a complete elimination of wastes managed by landfilling. However, this goal is not practicable for debris programs. Still, reducing the amount of landfilled wastes can make a significant difference in the debris mission, as existing landfill capacity can be rapidly overwhelmed in a large event.



FIG. 29.1 The Net Zero Waste Hierarchy Diagram.

3.2 Waste Segregation

Waste segregation is a critical first step in finding Net Zero opportunities and should be implemented as early as possible and expanded as the debris mission progresses. Waste segregation allows for beneficial reuse and recycling and is important when handling hazardous or problematic materials. Curbside segregation has proven effective in the United States (Fig. 29.2). A flier is typically prepared and distributed to residents who require debris removal assistance, and this information is also shared on websites and social media sites. Compliance with the segregation is historically high, although there can be some oversights. Thus a secondary screening is generally implemented as well.

3.3 Waste Reduction

Considering the NZW Hierarchy Diagram (Fig. 29.1), the first consideration is waste reduction. Waste reduction in a conventional sense is to adopt practices that eliminate waste generation from occurring in the first place. This could, for example, include the use of electric hand driers to reduce paper waste in an office complex. Reduction is challenging in a debris mission. Whatever is generated during the disaster event must be addressed. Therefore conventional waste reduction is limited in a disaster response situation. However, volume reduction is a commonly used approach. This includes crushing large objects. For example, refrigerators (and other white goods such as washing machines, driers) are typically processed to remove spoiling food and refrigerant, then crushed (Fig. 29.3). These can then be landfilled, or better yet, send to a processing facility to allow for recovery of recyclable materials found in these.

Large storms like hurricanes typically generate massive quantities of vegetative debris. There are often opportunities to recycle a substantial portion of the vegetative material (see



FIG. 29.2 Curbside segregation of household hazardous waste and segregated electronic wastes, which were processed for recovery of materials (Hurricane Katrina) [5].

Section 3.5), but often the majority of the vegetative material must be disposed. Once again, reducing volume is critical. The most expedient means of reducing the volume of vegetative material is by incineration (Fig. 29.4). Open piles are a quick way to burn vegetation. These require little set up. The fire is usually maintained by forced air into the pile or by turning the pile with construction equipment. However, this approach can result in excessive air pollution, particularly by particulate releases. Air curtain incineration establishes a draft to pull the air through a simple particulate removal system. Air curtain incineration can be established by below grade trenches or using containerized equipment. Incineration is a fast and efficient

means to rapidly decrease the volume of dry vegetative material.

In addition, response to large disasters often involves large numbers of people converging to the affected area. These people can strain already overtaxed resources. Applying reduction approaches to waste generation for these people can help the recovery effort.

3.4 Repurposing

Repurposing involves finding new ways that a waste product could be used beneficially with little or no modification. One excellent example is finding constructive opportunities for the reuse of large woody debris, as



FIG. 29.3 Removal of refrigerant from refrigerators and crushing to reduce volume.



FIG. 29.4 Incineration of vegetative material. The left of open pile burning. The middle is a trenched air curtain and the right is a containerized air curtain system.

described in Channell et al. [5]. Unmanaged large woody debris (LWD) can clog streams and drainages, causing these to overflow and create local flooding issues. However, careful placement of LWD can be used to stabilize stream banks, reestablish channels, and reduce erosion (Fig. 29.5).

3.5 Recycling

Recycling can make a large impact in waste reduction. Brandon et al. [7] detail waste segregation and recycling efforts during the Katrina debris mission. Chipping vegetative wastes

reduces their volume and can promote recycling opportunities. A number of chipping equipment are available. A tub grinder is a very useful piece of equipment because it can be used on a range of debris matter (Fig. 29.6). Chipped vegetative material can be reused in several valuable ways, such as a soil amendment to control erosion, stock for paper factories, and as a landfill cover material. Chipped vegetative material can also be returned to the natural environment to reduce nutrient losses that are associated with the removal of storm debris. Chipped material can be incorporated with composting, creating a useful fertilizer for local recovery. It can also



FIG. 29.5 Large woody debris (LWD) removed from the stream bed and placed on the bank and mid-channel bar as a woody revetment to restore flow in the stream.



FIG. 29.6 Tub grinder, an effective tool to reduce volume of large debris materials, including chipping of woody vegetative material.

be used as a feedstock for energy production (see [Section 3.7](#)).

Contamination soils and sediments can be incorporated in asphaltic material and recycled as road materials [8]. Damaged concrete can be ground and used as a road base, in asphalt, or in new concrete. Separated materials, like metals and electronic goods, can be accumulated and sent for recycling. Often, the local infrastructure will not support these materials, either because the recycling businesses are damaged or, in some cases, these businesses are nonexistent in

the affected area. So, these often need to be shipped out. The shipping can add expense, but this can offset by the large quantities that are generated by storms.

3.6 Composting

Composting is described in Medina et al. [9]. It is a biological treatment process for organic constituents involving the placing of organic material in a pile with sufficient water and air to stimulate microbial activity. The pile creates insulation, which causes both a rise in temperatures and an increase in biological activity ([Fig. 29.7](#)). The temperature gradient within the pile stimulates air flow as the pile becomes a self-sustaining reactor. The end result of a successful composting treatment is a useful soil amendment that can be used as a fertilizer, to reduce erosion, as an amendment to degrade organic contaminants, or even as a landfill cover material.

Composting could be a valuable technology for addressing wastes associated with disaster debris. Composting typically uses vegetative materials, so it can be a useful means of recycling vegetative wastes found in debris. In addition, other organic materials can be addressed in the



FIG. 29.7 A forced air compost pile used to treat vegetative, food, and animal wastes.

composting process, including food wastes, dead animals, manure, sludge, and even human wastes (Fig. 29.8). During the composting process then volatile organic components are consumed, making the resultant material much less offensive than many of its components. In addition, the high temperatures are effective at deactivating pathogenic organisms, so the disease threat is minimized or eliminated. Composting can also be adapted for treating chemically contaminated soils, including those contaminated with petroleum products and explosives, so it could be coupled with soil or sediment remediation [8]. Composting is useful means of addressing a wide range of waste products.

Composting can, however, take time, requires maintenance, and can take space as well. These factors have limited the actual application of composting in disaster response situations. Still, its ability to address a wide range of waste constituents makes it worth consideration in a debris management scenario.

3.7 Waste to Energy

Conversion of waste to energy is considered a valuable way to reduce landfilled wastes. In the case of disaster response, energy infrastructure

is commonly damaged. Generation of energy from wastes could be an attractive option for the short term.

There are three main types of thermal destruction of organic wastes, each with different options for energy recovery (Fig. 29.9). The most common, commercial scale process is incineration or complete combustion. Stoichiometric, or excess, oxygen is introduced to the burning waste such that all the organic carbon gets converted to carbon dioxide. All the chemical energy in the waste is converted to heat which can power a steam turbine system for electricity production, or the heat could be applied to something like a Sterling engine at a smaller scale.

Gasification means thermal destruction with limited oxygen [10]. Instead of carbon dioxide, the organic carbon is mostly converted to carbon monoxide (a gaseous fuel) and some longer chain hydrocarbons, depending on the specific process. This process captures the energy content of waste input. The goal with gasification is to transform all the organic material into a flammable gas (syngas), which in turn can be burned in a generator typically with an internal combustion engine. Sometimes tars are also generated along with the syngas; these must be



FIG. 29.8 Comparison of initial (left) and finished compost (right) consisting of leaves, pine straw, leaves, sludge, and food. Food is clearly visible in the initial compost (left), but almost completely degraded so as to be unrecognizable in the finished compost (right).

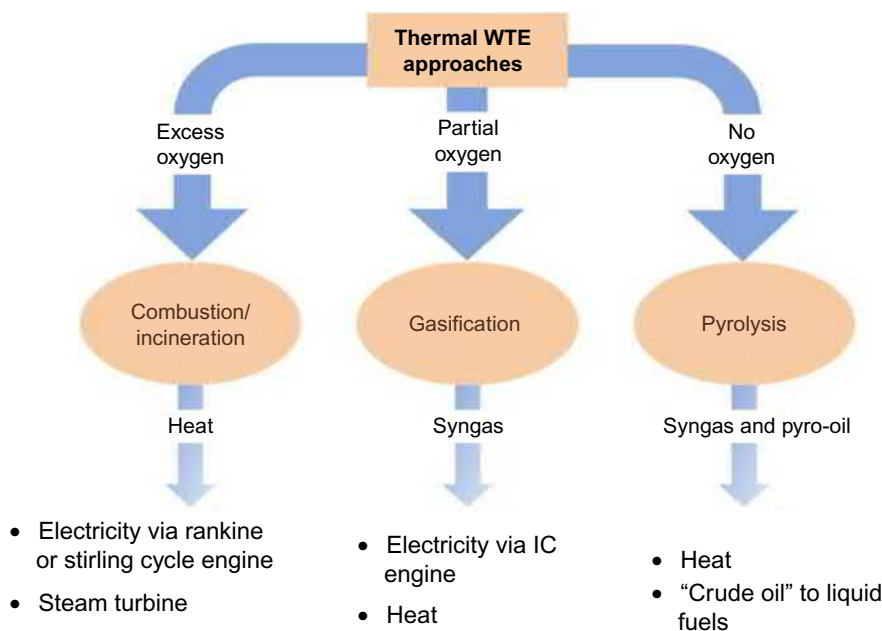


FIG. 29.9 Thermal waste to energy approaches.

removed from the gas stream before conversion to energy. In remote or smaller areas, gasification makes the most sense because this process can covert waste to electric energy in a relatively few steps, with only inorganic ash residue. Pyrolysis means thermal destruction of organic compounds with no oxygen. Pyrolysis produces syngas and oils. Researchers are working on processes to convert the pyro-oils to fuels or other useful chemicals; there is limited potential to use the pyro-oil directly.

Anaerobic digestion is a biological means of processing wastes that can generate energy [11, 12]. Wastes are digested in a reactor that anaerobically, forming methane gas that can be used for fuel. Anaerobic digestion has the advantage that it can be effective for wet wastes, including spoiling food, manure, and even human wastes. Like composting, the anaerobic treatment process, the offensive aspects of these wastes can be mitigated.

There are, however, limitations that have minimized the application of waste to energy

applications in debris missions to date. Transportable systems are few in number and these tend to be relatively small in energy capacity. They take time to set up, the fuels generated by each of these processes are generally inferior to that of refined petrochemicals and may therefore require processing for use in existing energy production equipment. Furthermore, many of the systems actually require some fuel, usually diesel, to create favorable conditions for reactions to occur. For now, waste to energy is a promising, but still unrealized, technology for addressing debris wastes.

4 DEBRIS MISSION—HURRICANE IRMA AND MARIA

4.1 Background

In September of 2017, Hurricane Irma, followed by Hurricane Maria, caused severe damage in Florida and several Caribbean Islands,

such as Puerto Rico, Dominican Republic, Saint Maarten, and U.S. Virgin Island (USVI). Both these catastrophic storms reached category 5 in the open sea and both made landfall at category 4. The combined effect of these storms resulted in hundreds of lives lost and left thousands of people homeless. Most of the islands were without power for several months.

The primary focus of this section is on the Debris Mission performed in USVI and Puerto Rico. Upon the landfall of these storms, FEMA with the support from the USACE and the U.S. Environmental Protection Agency (USEPA) arrived to the most affected areas in both islands to support this mission. Approximately $1.5 \times 10^6 \text{ m}^3$ (2 million yd^3) of debris were removed from the USVI, while more than $4.6 \times 10^6 \text{ m}^3$ (6 million yd^3) were managed in Puerto Rico. USACE managed the entire debris mission in the USVI and it managed $3 \times 10^6 \text{ m}^3$ (4 million yd^3) in Puerto Rico, with the balance being managed by local entities. The USEPA was in charge of collecting hazardous waste. As the mission progressed, different types of debris were generated due to the damaged appliances and the mold growth in buildings creating an increment in construction and demolition (C&D) debris.

The debris mission was to remove, collect, and dispose the generated debris following the disaster to eliminate immediate threat to life and public health. The removal operations were divided by public and private property ensuring clearance of roadways in the vicinity of critical public facilities.

4.2 Debris Types

The initial trash and debris estimated for Maria in Puerto Rico was $4.7 \times 10^6 \text{ m}^3$ (6.2 million yd^3), of which 70% was vegetative debris, 25% C&D, and the rest was mostly garbage. FEMA obligated more than \$1.4 billion in total funding just to Puerto Rico for debris removal and emergency protective measures. Affected

counties in the United States were later reimbursed for Irma Debris removal in the affected areas.

The following debris types were part of the USACE mission:

- vegetative debris: trees, trees stumps, branches, trunks, and other leafy material;
- C&D: lumber and wood, gypsum wallboard, glass, metal, roofing material, tile, carpeting and floor coverings, window coverings, pipes, concrete, fully cured asphalt, equipment, furnishings, and fixtures (can be recycled);
- white goods: refrigerators, freezers, air conditioners, heat pumps, ovens, ranges, washing machines, clothes dryers, and water heaters;
- household hazardous waste: paints, stains, containing volatile chemicals that catch fire.

In addition, vehicles and vessels were also assigned to USACE by the end of October of 2017. Soil, mud, sand, putrescent debris, and infectious waste were assigned to other organizations for this mission. The garbage generated from the storm was collected by the Department of Solid Waste Management. [Figs. 29.10 and 29.11](#) show debris from Hurricane Maria in Humacao and North Camuy in Puerto Rico (pictures taken by USACE crew during mission).

4.3 Debris Mission

The magnitude of two closely spaced hurricanes coupled with logistical challenges of the response mission slowed the debris response mission. Consequently, piles of debris accumulated for weeks within the islands. The USACE mission in USVI was completed by the end of March of 2018, but the one in Puerto Rico was extended until mid-April of 2018. Lack of landfill space required that landfills had to be overfilled beyond their capacity and sports stadiums were used as temporary landfills.



FIG. 29.10 Piles of debris awaiting for pick up in Humacao, Puerto Rico.

Debris removal was designed in three phases

- phase one—clearance to open access for emergency response vehicles and necessary traffic;
- phase two—removal of debris affecting health and safety, and debris removal as means to recovery;
- phase three—other actions necessary to protect health and safety, which may include, but not limited to, pest or dent control activities associated with the presence of debris.

Plans were made to dispose most of the debris in Puerto Rico locally. However, hazardous

wastes would have to be disposed of in the continental United States. In addition, most recyclable metals and electronic materials will also have to be taken to the United States. Most of the debris from USVI had to be removed from the territory by barge. Shipping wastes to the US mainland was complicated by the threat of invasive species and transportation cost.

4.4 Debris Removal Over Time

The weekly yardage collection from Hurricane Maria is shown in [Fig. 29.12](#). The removal mission took 27 weeks or more than half a year.



FIG. 29.11 Beach debris in Northern Camuy, Puerto Rico.



FIG. 29.12 Debris collection from October 12, 2017 to April 19, 2017.

The debris recovery initially steadily increased as man power was added, processing centers were set up, and collection procedures were optimized. Collection peaked in weeks 12 and 14, but there was a dip in week 13 due to the Christmas holidays. From weeks 14 to the end of the mission, the debris collection steadily declined, as easy to collect materials were removed, leaving more challenging debris to be removed.

Fig. 29.13 separates the debris into key types. Initially, removal focused largely on the removal of vegetative waste and C&D materials. Removal of vegetative materials peaked from mid-November to mid-December. Vegetative removal exceeded removal of other materials from early November to mid-January. At that point, removal of C&D wastes began to exceed vegetative waste removal and this continued through the end of the project. C&D debris removal steadily increased to mid-January and then began to fall off in early February. Still, C&D debris remained the most significant waste form from mid-January to the end of the debris mission in April. Mulch began to be reported in

December and other debris types (fill dirt, logs, scrap metal, and tires) began to be reported in early January.

4.5 Problems

4.5.1 Limited Landfill Space

Landfill availability for debris disposal was extremely limited. Before Hurricane Irma and Maria, landfills in Puerto Rico were beyond capacity. In addition, some of these landfills had become toxic sites due to leachate problems; thus violating the federal environmental safety rules. Currently, Puerto Rico has only 27 landfills serving 78 municipalities, which some of those are not in compliance with the law. Some of these debris (for both storms) were stored in public places, such as schools, soccer fields, and any available area resulting in odor problems and health risks to nearby communities. Application of waste reduction measures, particularly incineration, helped reduce the volumetric impact. However, issues of landfill space are expected to affect both islands in the upcoming future.

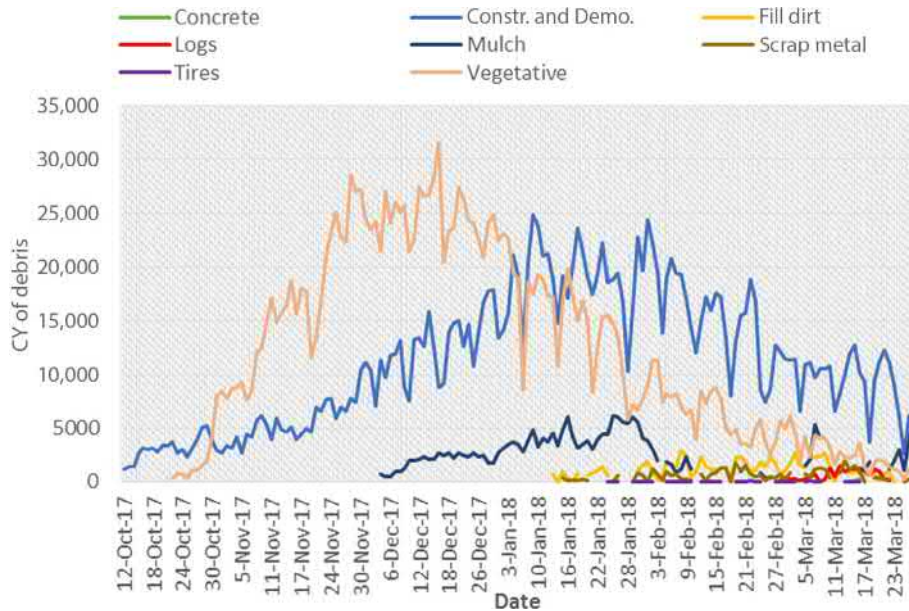


FIG. 29.13 Different types of debris collected after Hurricane Maria in Puerto Rico over the course of the debris mission.

4.5.2 Remoteness

The island nature of both Puerto Rico and the USVI affected the disaster response in general and the debris mission as well. The island nature made it challenging to bring in resources, including people. Resources for debris recovery had to compete with the need for supplies for the reestablishment of energy, repair of damaged water infrastructure, need for fuel, need for bottled water and food. The islands had limitations of housing and office space needed to conduct debris operations.

4.5.3 Rough Terrain

Although small, Puerto Rico is a mountainous island with more than 1200 m (4000 ft) of vertical elevation. The mountainous regions can have narrow and twisting roads. Many of these areas needed to be cleared to allow for the energy recovery mission to succeed. Clearing these areas took an inordinate amount of resources.

4.5.4 Continued Degradation of Damaged Building

As the lead of the disaster response mission, FEMA prioritized the most critical activities to address the most imminent needs. This meant that some areas had to wait before receiving help. In many cases, building were damaged, but could still be inhabited for the time being. However, in these tropical islands, rain continues as did the buildup of mold and other biological growth. As time went on, the damage to these buildings increased, often to the point that the structures had to be completely razed. The result was the generation of more C&D debris as time continued.

4.5.5 Marine Vessels

Damaged marine vessels were a critical problem for these islands, particularly the USVI. The U.S. Coast Guard aid in the removal of 479 displaced vessels. Disposal of these damaged vessels was managed by the USACE. Marine

vessel processing involves numerous steps including removal of fuels and fluids, removal of engines and metal, and cutting the damaged vessel into manageable pieces for disposal.

5 SUMMARY

In the United States, the Department of Defense has an important role in the nation's Federal disaster response mission. Through the USACE, the DoD fulfills the mission of debris removal. A key part of the debris mission is diverting or minimizing materials from being landfilled. Applying the principles of NZW are valuable in reducing landfilled wastes in the debris mission. The debris response mission following the 2017 Hurricanes Irma/Maria for the USVI and Puerto Rico illustrates the issues of finding sufficient space for debris processing and disposal, providing valuable lessons in making the debris mission more efficient.

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Space Waste

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1 INTRODUCTION

On February 10, 2009, at an altitude of 790 km over Siberia, two satellites collided at a relative velocity of 11 km s^{-1} [1], creating almost 2000 fragments larger than $\sim 10 \text{ cm}$ and many thousands of smaller fragments. Iridium 33, launched in 1997, was an operational communications satellite that was part of a constellation of 66 satellites that provide voice and data services worldwide. The other satellite was Cosmos 2251, a decommissioned communication satellite launched by the Commonwealth of Independent States (Russia) in 1993. This was a

landmark event in the history of orbital debris as it was the first accidental hypervelocity collision of two large, intact satellites.

Earth-orbiting spacecraft have become an integral part of our everyday lives. We depend on them for communications, weather forecasts, scientific research, and national security. However, space waste (also called space or orbital debris) is becoming a real and growing concern for the safety and reliability of these satellites. Even small particles can damage, degrade, or destroy spacecraft due to the very high velocities involved in a collision, on average about 11 km s^{-1} in low-Earth orbit (LEO), and a major

accident such as the Iridium-Cosmos collision of February 2009 can have long-term effects on the space environment around Earth.

Debris is now an operational concern and there have been several reported incidents. For example, the European Space Agency's radar satellite Sentinel-1A was hit by debris in August 2016. Its solar arrays were damaged and a disturbance to its attitude was detected [2]. Fortunately, the damage was relatively minor and the mission continues.

During the Space Shuttle program, incidents involving debris occurred at least twice: first with STS-7 in 1983 and later STS-115 in 2006. In both events debris impacted the spacecraft structure requiring further maintenance for reutilization. In 2016 debris impacts were identified on the International Space Station. A chip of 7mm diameter in one of the windows of the Cupola module was the result of a debris impact (Fig. 30.1). That event was most likely caused by a paint flake or other millimeter-sized fragment. In addition to shielding of specific modules, avoidance maneuvers and emergency measures are used to respond to a debris threat depending

on the risk level. The ISS performed 21 debris collision avoidance maneuvers from 1999 to early 2015 [3]. Even though these are not frequent, the cases in which the crew had to board the Soyuz TMA capsule and prepare to evacuate the ISS demonstrate the real dangers of space debris impacts.

2 THE CURRENT ORBITAL DEBRIS ENVIRONMENT

Satellites have been tracked for many years by national defense agencies. This capability is now also used to maintain catalogs of all the satellites, and fragments of satellites, which can be detected. Objects as small as 5 cm can be tracked in LEO, but only larger objects (0.3–1 m or more) are detectable in the more distant geosynchronous orbit (GEO, see Fig. 30.2). The most widely used database is that maintained by the U.S. Strategic Command's Space Surveillance Network (SSN) and available from www.space-track.org. Russia and Europe have independent monitoring capabilities, but these are not as

FIG. 30.1 Damage to the Cupola window of the International Space Station, about 7mm across; probably due to a paint flake impact (© ESA/NASA).



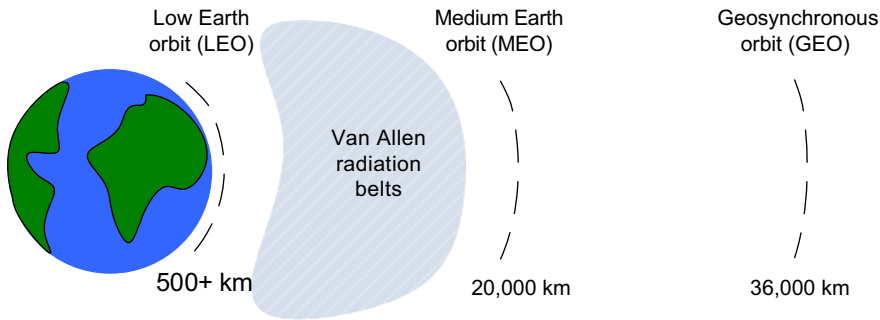


FIG. 30.2 The main orbits used around Earth. Most satellites are in LEO; MEO is used by GPS and other navigation satellites, and GEO is widely used for communications and TV broadcast.



FIG. 30.3 Image showing the distribution of space debris objects around Earth (© ESA, CC BY-SA 3.0 IGO).

capable as the US system. These surveillance tools show us the scale of the space waste challenge and help us to plan future action.

Around 20,000 objects are currently tracked using telescopes and powerful surveillance radars. Fig. 30.3 shows a representation of the space debris objects now around Earth (object sizes are much exaggerated to make them visible): the distributions follow the main orbits shown in Fig. 30.2. It is striking to remember that in 1957, when the first satellite, Sputnik-1, was launched, there was zero orbital debris. LEO has the densest population of debris, but there are significant amounts of debris in GEO too.

The amount of debris smaller than we can detect routinely is estimated statistically using data from several targeted experiments or observations. From these we believe there are around 750,000 objects in the range 1–10 cm, and millions of objects small than 1 cm [4].

2.1 The Debris Population

Fig. 30.4 shows how the population of tracked objects has developed since 1957 (when Sputnik-1 was launched). Tracked objects include operational (functional) spacecraft, non-operational (inactive or retired) spacecraft and

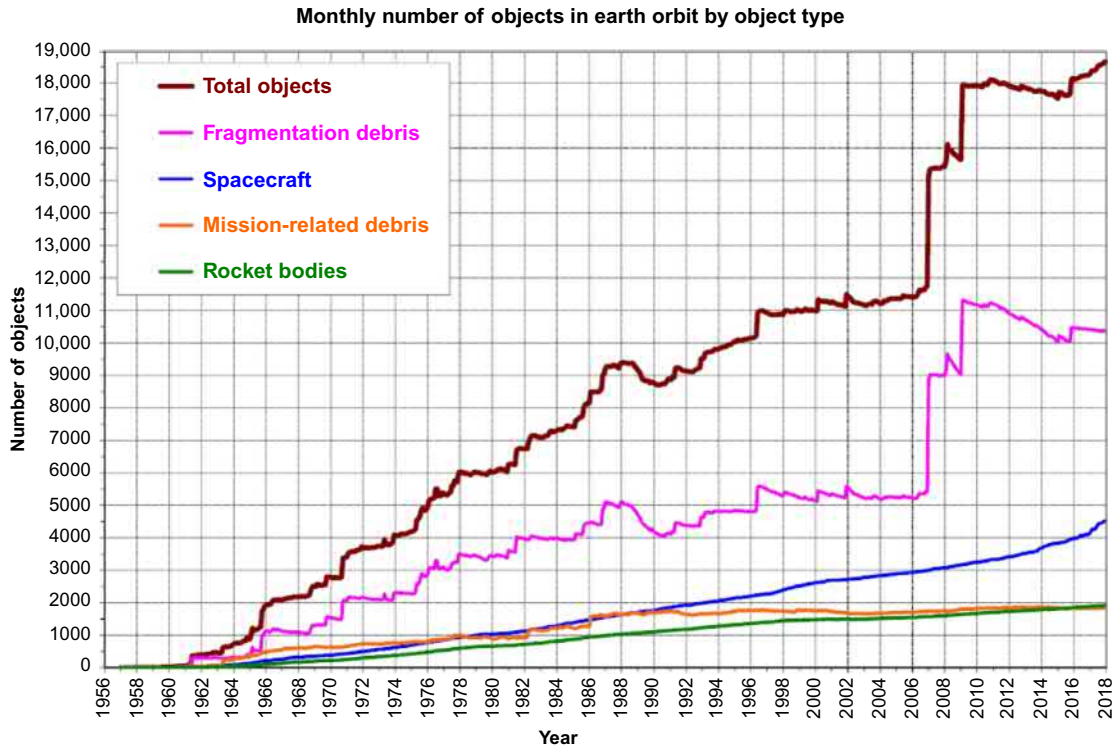


FIG. 30.4 Growth of the number of objects in Earth orbit from the SSN catalog (NASA [5], omitting militarily sensitive objects).

rocket bodies, as well as debris from a variety of sources. Any object that is not performing its intended function is considered to be orbital debris, including upper stages that have already delivered their payloads and spacecraft that are no longer functional. Only around 1000 of the tracked objects are functioning spacecraft.

There are two significant increases in the number of fragmentation objects in Fig. 30.4, in 2007 and 2009. Just these two events (the Iridium-Cosmos collision already mentioned, February 2009, and a Chinese antisatellite missile test, January 2007) more than doubled the number of fragmentation objects being tracked. The deliberate destruction of the Fengyun-1C weather satellite (in a circular orbit near 850 km) in January 2007 caused the single largest fragmentation event in space (to date) with more

than 2600 cataloged fragments (it was a test/demonstration of a direct ascent antisatellite weapon).

Orbit height has a huge influence on the expected lifetime of debris objects around Earth. Fig. 30.5 shows predicted lifetimes for LEO satellites in circular orbits, for two characteristic satellite densities (less dense objects deorbit more quickly). Note that even within the LEO region (which conventionally extends up to a height of 2000 km), some satellites are expected to stay in orbit for over 20,000 years, that is, more than the time since the last ice age. Even for the popular orbit heights of 800–1000 km, the lifetimes are measured in centuries, and hence the two major fragmentation events which were in this band could remain a problem for generations to come [6, 7].

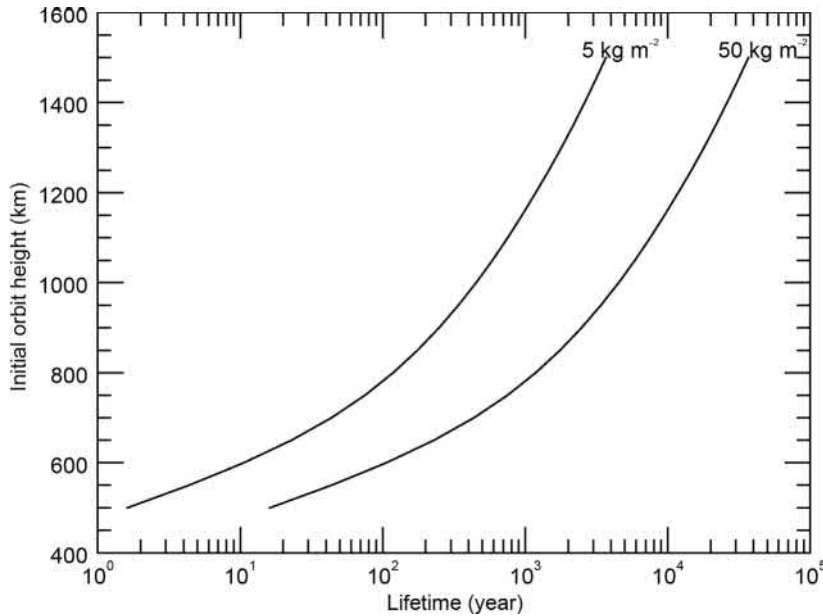


FIG. 30.5 Predicted lifetime for objects in circular orbits with different initial orbit heights, and for two representative areal densities (expressed as ballistic coefficient $B = m/C_D \cdot A$, where m is mass, C_D is drag coefficient, and A is the projected area, using the MSIS86 model for atmospheric density).

2.2 Distribution of Orbital Debris

Fig. 30.6 shows the spatial density of orbiting objects as a function of altitude. The region below 2000 km altitude, LEO, is a natural divide since the spatial density drops significantly above this altitude. Altitudes near 20,000 km are home to the GNSS constellations (GPS, GLO-NASS, Galileo, and Beidou) used for navigation. The spike in spatial density near 36,000 km shows the location of geosynchronous altitude, where the satellite orbit period is 1 day, keeping the satellite over the same region of Earth.

The peak spatial density is near 800 km altitude, with a value of $4 \times 10^{-8} \text{ km}^{-3}$. This is the region where collisions are most likely between cataloged objects (and also where the Iridium-Cosmos collision happened). Further major collisions are expected every 5–10 year at present. If the rate of creating debris objects through collisions exceeds the rate of object removal (e.g.,

orbit decay) at any given orbit height then an accelerating, runaway, debris-creation cascade occurs. This catastrophic situation is termed the Kessler syndrome (after an author of the article which first formally described this case [8]). The runaway cascade builds gradually, but the conditions exist for it to be starting in several useful orbit regions.

Fig. 30.7 shows the distribution of the inclination of LEO objects in the USSTRATCOM catalog (perigee below 2000 km and eccentricity less than 0.3). The main peak (around 100 degrees) represents the satellites launched into sun-synchronous orbits (and their debris). These orbits cross the polar regions every orbit, increasing the local number density, and thus collision probability: it is no coincidence that the Iridium-Cosmos collision took place at high latitude.

Although satellites are launched into specific inclinations, visualizations of the locations or motions of satellites in LEO suggest a random

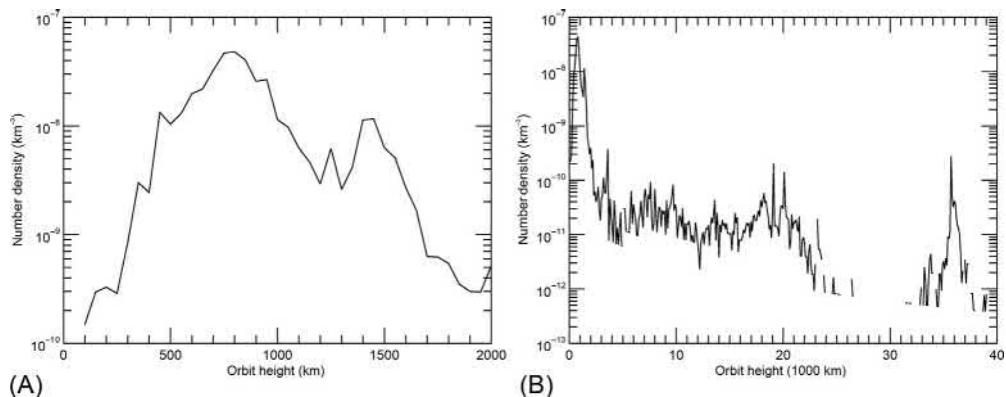


FIG. 30.6 Spatial density of objects as a function of altitude (estimated from semimajor axis, based on the SSC database, March 2018). (A) Low Earth orbit (averaged over 50 km in height). (B) Orbit heights up to 40,000 km (averaged over 100 km in height).

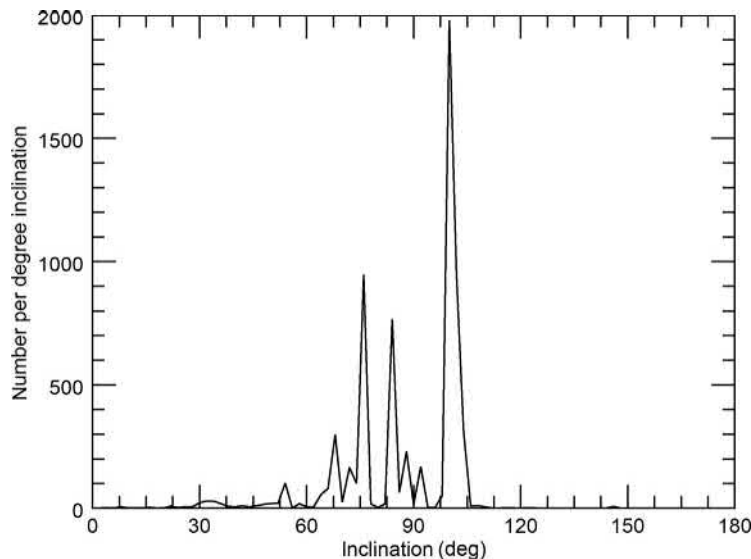


FIG. 30.7 Distribution of object inclinations in LEO (based on SSC data, March 2018, average over 2 degrees intervals).

distribution (see Fig. 30.3). After a collision, the fragments each acquire a small random velocity change which over time couples with orbit dynamics to spread the objects out almost randomly.

The behavior of objects is somewhat different in GEO. Typically, operational satellites are

placed into GEO at 0 degrees inclination at a specific longitude. At the correct altitude, the orbit period matches the rotation rate of the Earth, and with very small maneuvers, the satellite is kept stationary over the equator at that longitude. However, once the fuel runs out the object's orbit will start to change. The orbit

inclination will evolve over time and oscillate around a $7\frac{1}{2}$ degrees inclination stable orbit due to the Earth-Moon-Sun configuration (see Fig. 30.3). Objects released from 0 degrees inclination will increase in inclination to a maximum of ~ 15 degrees and then return to 0 degrees again over a period of ~ 52 years [9]. The objects will also drift in longitude, bringing them near to other objects in the GEO region. The collision speeds in GEO are an order of magnitude less than in LEO, leading to different types of collisions and resulting debris fragments.

2.3 Sources of Orbital Debris

As Fig. 30.4 shows, the debris population consists of several types of object. Active spacecraft are only $\sim 5\%$ of the total population. The main categories are discussed in the following sections.

2.3.1 Fragmentation Debris

On-orbit fragmentations can result from accidental or intentional explosions, accidental or intentional collisions, or aerodynamic forces as an object nears atmospheric reentry. More than half of all the USSTRATCOM cataloged objects are fragmentation debris. Since the first recognized fragmentation in June 1961, more than 200 satellites have experienced on-orbit breakups (excluding aerodynamic breakups). Most of the fragmentations have been the result of explosive release of stored energy: unused propellant, pressurized gasses, or batteries. Aerodynamic breakups, while relatively common, produce very few long-lived debris and are not important in the long-term orbital debris problem. Collisions, both deliberate and accidental, have been rare, but have created some of the larger debris clouds, including the largest single debris producing event to date, destruction of the Fengyun-1C satellite. Table 30.1 lists the 10 objects contributing most debris fragments to the SSD catalog as of March 2018.

Most of the satellite fragmentations have occurred in LEO or for highly elliptical orbits that

TABLE 30.1 Top 10 Orbital Debris Producing Events in the SSD Catalog for March 2018

Rank	Total Objects	Debris Name	ID	Typical Height (km)
1	2603	Fengyun 1C	99025	850
2	1033	Cosmos 2251	93036	740
3	454	NOAA 16	00055	840
4	394	Cosmos 1275	81053	940
5	315	Iridium 33	97051	730
6	293	Thorad Agena D	70025	910
7	224	Delta 1	75052	1160
8	219	DMSP 5D-2 F13	95015	820
9	191	Delta 1	73086	1500
10	189	SL-16	92093	870

The ID indicates the year of launch (first two digits) and the sequential launch number for that year; hence Fengyun-1C (99025) was the 25th launch of 1999.

pass through LEO (due to the higher spatial density in this region). Only two known breakups have occurred in GEO: a Titan transtage rocket body (International Designator 1968-081E) that delivered the OV2 satellite, and the EKRAN 2 satellite (1977-092A). However, some surveys of GEO indicate that there may be additional breakups in the region [10]. No known breakups have occurred in the medium Earth orbit (MEO) region used by navigation satellites.

In the early and mid-1970s, Delta launch vehicle second stages were left in orbit with residual fuel onboard. Over time, thermal stresses caused by the passage into and out of the Earth's shadow would rupture the common bulkhead between the propellant and oxidizer tanks, resulting in an on-orbit explosion. Eight of these stages were launched in this configuration prior to recognition and correction of the problem.

The last of these exploded in 1991. Correction of the problem by venting any residual fuel, once on-orbit, was one of the early successes of orbital debris mitigation efforts [11].

The problem with residual fuels was eventually recognized by all launch operators. In 1986 the SPOT 1 and Viking satellites were launched into sun-synchronous orbits by an Ariane 1 rocket. Nine months later the Ariane upper stage exploded, likely due to residual fuels left onboard [12]. This event led to improved cooperation and information exchange on orbital debris among various national space agencies, leading to the eventual creation of the Inter-Agency Space Debris Coordination Committee (IADC).

2.3.2 Mission-Related Debris

Mission-related debris are objects intentionally discarded during satellite delivery or satellite operations. These include lens caps, separation and packing devices, spin-up mechanisms, empty propellant tanks, and a few objects thrown away or dropped during human activities. New missions are now designed to avoid creating this class of debris.

2.3.3 Anomalous/Deterioration

As spacecraft spend many years in the harsh space environment, many deteriorate and start to release degraded material fragments or parts. This creates what is referred to as “anomalous debris.” An anomalous event is the unplanned separation, usually at low velocity, of one or more detectable objects from a satellite which otherwise remains relatively intact [13].

The disintegration of spacecraft exterior paint is thought to create many submillimeter pieces of debris. The cause of this paint flaking is thought to be radiation effects and/or atomic oxygen erosion of the organic binder in the paint. This erosion is another major source of small debris in LEO. Stage and spacecraft separation processes that occur in orbit also frequently release small debris.

2.3.4 Slag/NaK/Other

Many small orbital debris particles are created by solid rocket motor (SRM) firings, which produce aluminum oxide (Al_2O_3) particles called slag. These particles are formed especially toward the end of a burn (tail-off), by the rapid expansion, distribution, and solidification of the molten Al_2O_3 slag accumulated during the burn. Since the transfer orbits are elliptical orbits, most of the particles reenter quickly because of atmospheric drag at the orbit perigee. However, the propensity of SRMs to generate particles of 100 μm and larger has caused concern regarding their contribution to the debris environment. Particle sizes as large as 1 cm have been witnessed in ground tests, and comparable sizes have been estimated via ground-based and in situ observations of suborbital tail-off events [14]. Due to the large number of particles ejected by each motor, these Al_2O_3 particles can represent a significant surface erosion and contamination threat to spacecraft.

Another class of debris is the sodium-potassium (NaK) droplets that were released from Radar Ocean Reconnaissance SATellite (RORSAT) spacecraft launched between 1971 and 1988 by the former Soviet Union. On a number of RORSATs, the nuclear reactor core was ejected from the spacecraft, which apparently caused a breach in the NaK cooling loop. The liquid metal NaK spewed out and formed spherical droplets. Very few of the drops were large enough to be detected by ground sensors until statistical measurements of the environment with the Haystack and Goldstone radars in the 1990s. There may be over 50,000 NaK droplets that are 5 mm or larger in orbit today [15].

3 MITIGATION, ADAPTATION, AND REMEDIATION

The space community has now recognized the challenge posed by space debris and is starting to implement mitigation, adaptation, and remediation actions:

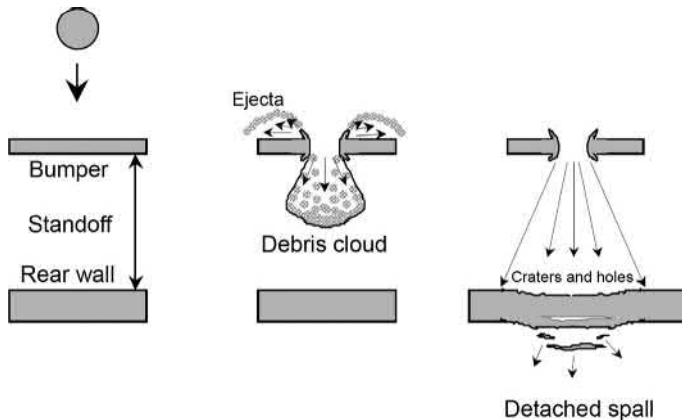


FIG. 30.8 Principle of a simple Whipple shield [16]: an impacting hypervelocity particle is fragmented by the bumper so that the rear wall is not perforated (although it may be damaged) by the resulting debris cloud.

- Mitigation concerns (a) preventing the creation of future debris and (b) limiting the long-term presence of new space objects in particularly useful orbit regions.
- Adaptation is to modify spacecraft designs and operations to suit the current space debris environment.
- Remediation is dealing with the existing space debris population to minimize future risks.

Studies suggest that all are needed. Despite the rapid increase in the number of debris in orbit, the absolute risks to operational spacecraft from collisions with man-made debris remain low for the moment. However, the threat to the approximately 1000 operational satellites now in orbit around the Earth increases with the growth of the orbital debris population.

Adaptation and Mitigation are discussed in this section; Remediation is discussed later.

3.1 Adaptation: Shielding Against Orbital Debris

Small, untracked debris, due to their very large numbers, pose the greatest threat to operational spacecraft. The structure of satellites provides some protection from the smallest orbital debris, that is, less than 1 mm. Most satellites

are vulnerable to impacts from particles in the millimeter-class size regime and larger. It is possible to design shielding to protect a spacecraft against impacts with objects up to ~ 1 cm in size; however, it is impractical to carry shielding able to protect against larger objects.

The Whipple shield was the first spacecraft shield ever implemented. It is lightweight and very effective against hypervelocity impacts with small objects (Hypervelocity means impact speeds which exceed the speed of sound in the material, so that shock waves dominate the collision process: this is the case for most LEO collisions). The shield design was suggested by Fred Whipple as early as 1947 [17] and is still in use today. A simple Whipple shield consists of a thin “sacrificial” wall mounted at a distance from a rear wall (Fig. 30.8). The function of the first sheet or “bumper” is to break up the projectile into a cloud of material containing both projectile and bumper debris. This cloud expands while moving across the standoff, resulting in the impactor momentum being distributed over a wide area of the rear wall. The back sheet must be thick enough to withstand the blast loading from the debris cloud and any solid fragments that remain. For most conditions, a Whipple shield results in a significant weight reduction over a single plate.

Shielding technologies have advanced considerably beyond the simple Whipple shield.

For example, the Stuffed Whipple shield has layers of Kevlar and Nextel sandwiched between the outer and inner walls. This increases the effectiveness of the shield and decreases the stand-off distance needed between the two walls. The latest concepts for improved orbital debris shields involve replacing typical Whipple stuffing materials and aluminum honeycomb with new metallic foams. These new designs offer greater protection from the meteoroid and orbital debris environments with less overall structural mass [18].

The International Space Station (ISS) is the most heavily shielded spacecraft in history. Since the orbital debris environment presents a very asymmetric flux to the ISS, not all critical surfaces need the same level of protection. Therefore the ISS employs hundreds of different, custom-made shields to protect critical components of the extensive structure, including habitable compartments and vital external units and lines, and to minimize the volume and mass of the shields.

3.2 Collision Avoidance

Collision avoidance serves both adaptation and mitigation. A major collision would create much additional debris and so avoiding collisions benefits the whole space community, however as the debris population increases avoidance becomes increasingly necessary. After the Iridium-Cosmos collision in early 2009, the Joint Space Operations Center of the U.S. Strategic Command started conducting conjunction assessments for all operational spacecraft in Earth orbit, regardless of ownership. Any prediction of a close approach, typically within 1 km, will be shared with the spacecraft owner/operator freely and immediately [19]. This helps everyone.

Due to inherent uncertainties in space surveillance measurements, the dynamic state of the atmosphere and, in many cases, the instability of at least one of the conjuncting objects, predictions of the collision of two satellites are

probabilistic. Typical maneuver probability thresholds for collision avoidance are 1 in 10,000 for human space flight and 1 in 1000 (or more) for robotic satellites.

Collision avoidance maneuvers normally integrate well with standard satellite operations. Collision avoidance maneuvers are typically very small, that is, involve changes in velocity of less than 1 m s^{-1} and in most cases can be conducted in a manner that does not waste propellant resources. For example, collision avoidance maneuvers performed by the ISS almost always result in a small increase in orbital altitude and thus simply constitute an unscheduled antidrag maneuver. Similar procedures are used for robotic satellites.

Collision avoidance is helpful for reducing the risk of collisions between tracked objects. However, over 99% of the risk to operational spacecraft comes from collisions with objects too small to track routinely, that is, objects smaller than 5–10 cm. Hence, only an improvement in the orbital debris environment itself can dramatically reduce collision risks for operational spacecraft.

3.3 Mitigation Policies and Practices

The international space community accepts that space debris is a threat to our continued use of many useful orbits. Agreement has developed around a set of actions and precautions that should be implemented to help manage the risks from space debris, and these now influence the way that nearly all spacecraft are designed and operated. The current policies and guidance have evolved from concerns which were first expressed at least 40 years ago.

One of the first comprehensive sets of orbital debris mitigation recommendations was issued by the American Institute of Aeronautics and Astronautics in 1981. Orbital debris mitigation was first mentioned in President Reagan's National Space Policy in 1988 and has been in each subsequent Space Policy. Following the first US government interagency report on

orbital debris in 1989, NASA issued the first formal orbital debris mitigation guidelines for a US government agency in 1995. These guidelines served as the basis for the U.S. Orbital Debris Mitigation Standard Practices, which were adopted in 2001 after a multiyear coordination with the US aerospace industry [20].

International coordination of space debris mitigation is represented by the Inter-Agency Space Debris Coordination Committee (IADC), founded in 1993. The IADC includes the space agencies of all the major space nations (and the European Space Agency) and has coordinated scientific research and policy development to achieve international consensus around a set of best practices in spacecraft design and operation. The IADC has published space debris mitigation guidelines (revised as [21]). These were submitted for consideration to the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space (UN COPUOS). After several years of debate and negotiations, these space debris mitigation guidelines were accepted by the United Nations in 2007. In parallel, the guidelines have been translated into practical engineering standards by the International Organization for Standardization (ISO) and are available as ISO 24113:2011 and related documents.

The IADC Space Debris Mitigation Guidelines [21] emphasize four major areas:

- (1) limitation of debris released during normal operations;
- (2) minimization of the potential for on-orbit breakups during and after space operations;
- (3) postmission disposal recommendations for vehicles in LEO, GEO, and other orbital regimes;
- (4) prevention of on-orbit collisions.

The first area concentrates on avoiding the creation of mission-related debris as discussed before. In the last decade, the absolute number of mission-related debris in Earth orbit has declined due to increasing adoption of design modifications.

The second area concerns the potential for on-orbit breakups during and after space operations. Prior to the collisions of 2007 and 2009, the greatest source of debris in orbit was from violent explosions of spacecraft and rocket bodies. The IADC guidelines advise depleting all significant energy sources onboard a satellite at the end of its active mission to avoid subsequent explosive fragment generation. This also is now widely (but not comprehensively) practiced.

The third area involves moving spacecraft and orbital stages out of active orbital regions after their useful lives have ended. The ultimate objective is to reduce the probability of creating additional debris from collisions in these regions. Spacecraft and orbital stages should be removed from LEO within 25 years of their end of mission, typically using orbits which lead to atmospheric reentry. Those operating in or near GEO should be placed in "graveyard" orbits (at least 200 km above or below GEO), which prevent them from drifting back within this GEO protected region for at least 100 years.

Much ingenuity is being devoted to developing ways to move satellites at their end of mission. The simplest is to reserve enough fuel for this, but many satellites have no propulsion and even for those which do it is difficult to decide when to deorbit due to uncertainties in fuel measurement and deteriorating satellite health at end of life. Other methods suitable for satellites without (functioning) propulsion include tugs and for some low Earth orbits there are technologies such as electrodynamic tethers and deorbit sails. No single technology manages all cases.

The fourth topic of space debris mitigation is active collision avoidance already discussed in [Section 3.2](#). Increasingly, space launch operators also use conjunction assessments to avoid colliding with a resident space object during the initial few hours of orbital insertion and deployment of new missions.

The IADC guidelines are not generally legally enforceable, although an increasing number of countries have incorporated them into their space mission practices. For example,

a United Kingdom mission will not be granted a launch license unless it can be demonstrated that adequate precautions consistent with the IADC guidelines have been implemented. US government and commercial missions must also follow national equivalents of these guidelines. France has gone further and made debris mitigation a legal requirement for its satellites.

4 REMEDIATION: DEBRIS REMOVAL TO PREVENT GROWTH

Predictions of the debris population over the next two centuries suggest strongly that the proposed mitigation measures on their own are not sufficient. [Fig. 30.9](#) [22] shows predicted debris population growth from 2010 to 2210 using the NASA LEGEND model (*LEO-to-GEO Environment Debris* model). These figures demonstrate (1) the value of mitigation, and (2) that remediation to actively remove some existing debris is needed. Comparing the sum of total numbers of debris objects at the end of the simulations (2210) for [Fig. 30.9A](#) (LEO + MEO + GEO) and [Fig. 30.9B](#) (regular launches and 90% postmission disposal) shows that mitigation measures are very effective and are expected to reduce the debris population from perhaps 90,000 objects to less than 22,000. However, even this is not enough to prevent a self-sustaining cascade from developing from around 2050 onward. Active Debris Removal (ADR) is proposed to reduce the debris population using new missions to removing existing debris objects from orbit. Two options for ADR are shown in [Fig. 30.9B](#): removing two or five objects per year. From these simulations it appears necessary to remove at least five objects per year.

4.1 Active Debris Removal

The broad conclusion that ADR will be needed to prevent uncontrollable growth in the debris population is now generally accepted.

The questions of how many objects, which should be chosen, how shall we do it, when do we need to start, and who pays for it, are being actively debated.

The technical questions are not trivial, but are still the easiest to answer. From [Fig. 30.9B](#) it seems that around five objects per year should be removed from LEO. The priority objects are those most likely to cause future debris. We can only answer this question statistically, but in general the priority targets are objects with a high mass and in densely populated orbit regions (e.g., 800–900 km in LEO). A broad range of technologies is being studied to identify suitable ways of interacting with debris objects [23] but with no clear conclusion yet. [Fig. 30.10](#) shows initial results to assess the urgency for ADR missions: it suggests that delaying the start from 2020 to 2060 makes only a minor difference to the long-term outcome (about 10% more debris in LEO by 2210). However, there is no doubt that the earlier we start, the better.

No ADR mission has yet taken place, but the space industry globally is preparing for this and missions are likely within a few years. One of the first could be ESA's e.Deorbit mission [24] to remove the dead Envisat satellite from LEO. Envisat is a large satellite (8 tonnes) in the middle of a popular orbit region (765 km altitude): if it were to suffer a collision it could create thousands of debris fragments in an important orbit which would remain a hazard for decades to centuries. It is therefore a priority target, and an opportunity for ESA to develop and demonstrate ADR technology using one of its own satellites.

Remediation creates important challenges for the space industry. Some challenges are technical, but perhaps the most difficult challenges are outside of engineering. The technologies needed for ADR could also be used aggressively to disable or remove an enemy's satellites. There must therefore be trust between all the space nations that ADR actions are genuinely that. There are concerns about the ownership of dead satellites, about an operator's liability if ADR tasks are

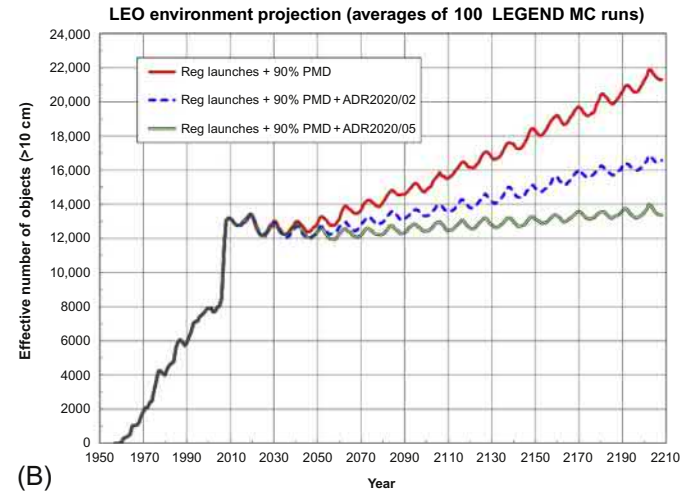
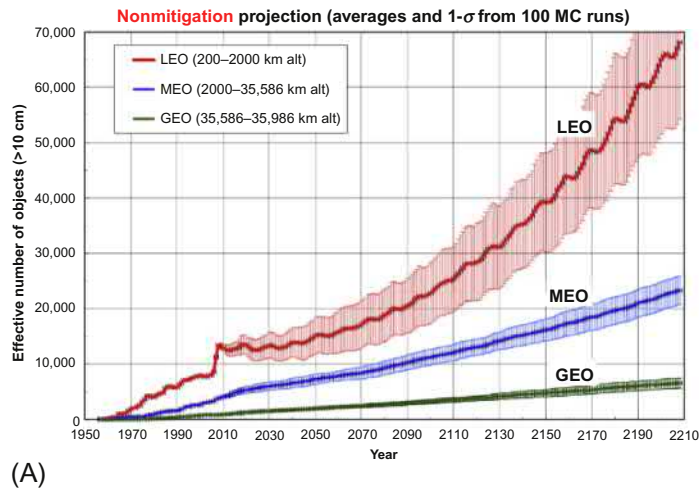


FIG. 30.9 Predicted evolution of the debris population [22]. (A) Debris population in different orbit regions with no mitigation (mean and 1 st. dev. uncertainties of 100 Monte Carlo simulations). (B) Debris population assuming mitigation and three ADR scenarios.

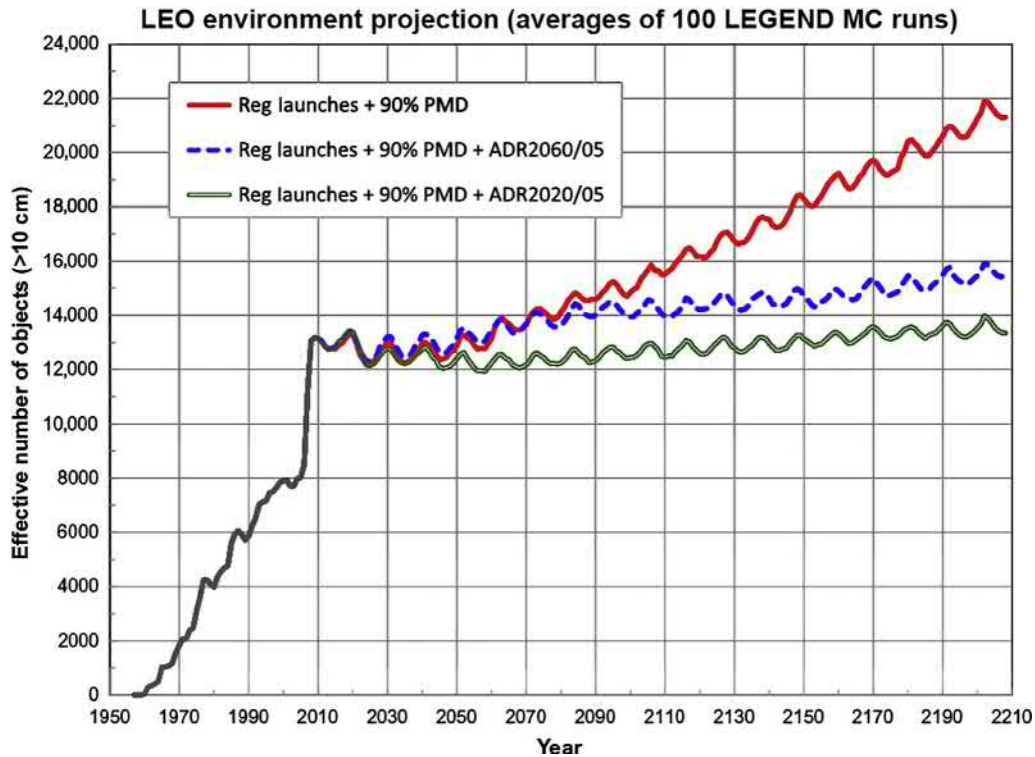


FIG. 30.10 Predictions of LEO debris increase with no ADR, or ADR of five objects per year starting in 2020 or 2060 [22].

unsuccessful or actually cause harm to other space objects, and ADR has to be paid for. Studies so far suggest that ADR for large objects is not much cheaper than the cost of the initial mission which created the debris. All these questions (technical, scientific, legal, commercial, economic, political) are being actively debated within the global space community.

5 REUSE AND RECYCLING?

As we look further ahead, long-term sustainable use of space encourages us to consider reuse and recycling of space assets (we increasingly do this for terrestrial waste, why not in space?). What would this mean?

Existing space assets represent a significant investment and so, unsurprisingly, there have

been many proposals to extend their useful life or to repair failed satellites. These activities fall under several related themes:

- life extension (e.g., refueling),
- servicing (initially using astronauts, but expected to be robotic in the future),
- space tugs (to maneuver existing satellites and/or restore functionality),
- manufacturing and remanufacturing (including recycling old satellites).

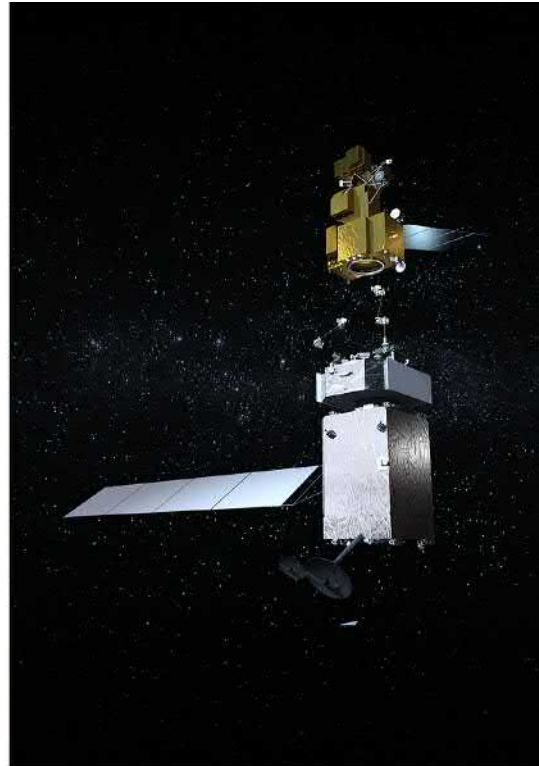
These activities overlap with ADR and share many of the same concerns (both technological and operational). Manned servicing missions using the Space Shuttle were performed for Solar Maximum (1984), Westar-6 (1992), and the Hubble space telescope (1993–2005); however, these missions were largely to demonstrate

TABLE 30.2 Some Proposals for On-Orbit Servicing Missions

Servicer	Servicer Operator	Client Operator	Method	Launch	Ref
MEV	Space Logistics Services (Orbital ATK)	Intelsat	Tug extension	2018	[26, 27]
Space Drone	Effective Space Solutions	Undisclosed	Tug extension	2018	[28]
Restore-L	NASA	Landsat-7	Refueling	2020	[29]
RSGS	SIS (SSL/MDA-DARPA)	SES	Tug extension Refueling	2021	[30]



(A)



(B)

FIG. 30.11 Example servicer-client mission concepts. (A) RSGS—Robotic Servicing of Geostationary Satellites (SSL, a Maxar Technologies Company). (B) NASA's Restore-L satellite (NASA/Satellite Servicing Projects Division).

capability and have not been repeated since. Technology demonstration missions for refueling have flown [25] and an increasing number of commercial proposals for on-orbit servicing are being developed (Table 30.2, Fig. 30.11).

The challenges for all these missions are (1) to develop the technology needed for semiautonomous rendezvous, docking and servicing, and (2) to find an acceptable business model for the mission. The need for a clear business model

tends to focus attention on the GEO region since many commercial missions operate there and also because it is relatively easy to maneuver between satellites and so to serve many clients (the higher orbit speeds and wider variety of orbits make this much more difficult in LEO). Servicing is much easier if the client “cooperates”: this can mean using a modular design and standard interfaces so that subsystems can easily be replaced, that is, design for servicing.

There needs to be a strong business model (not necessarily a commercial business model) for servicing and reuse to have a significant impact on space waste. This is still some way off for Earth orbit. It seems most likely that it could develop in GEO, and perhaps for some of the proposed mega-constellations in LEO (with many identical satellites in similar orbits), but even for these cases the legal and institutional frameworks to allow this barely exist yet. Nevertheless, ADR is increasingly recognized as an urgent need for the space community and the technologies and practices developed to enable ADR are exactly those which will make servicing and reuse of old satellites more feasible.

6 CONCLUSIONS

Films such as WALL-E and Gravity provide a pessimistic view of Earth’s space debris environment. We are far from this in reality and debris is still a minor cause of space mission failures. However, the predictions are clear that by around 2050, we will either have found ways to actively manage the space debris environment or we will have started to lose control of some orbit regions as a natural collision cascade takes off.

The global space industry is in a particularly dynamic period, with several transformative trends all developing in parallel. New commercial launch systems such as those of Space-X are being developed; mega-constellation projects

(e.g., OneWeb) are under development, and the smallsat/cubesat revolution is still underway. India and China are developing significant capabilities alongside the more established nations. These trends all tend to exacerbate the challenge of space waste.

There are serious challenges related to space debris and the problem inherently involves the full range of space disciplines: science, engineering, economics, policy, law, and with dimensions of international politics and the possible militarization of space. It seems clear that future progress will continue to depend on mutual trust between the main interested parties as well as the development of challenging technology. Orbit lifetimes measured in thousands of years or (much) longer for some orbit regions add a new perspective to our actions. Near-Earth space is a valuable common asset for all on planet Earth. We are still learning what sustainable development means in space, but it is a challenge we have started to tackle.

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Hazardous Wastes

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1 INTRODUCTION

The difference between a hazardous waste and nonhazardous waste is arguably situational. The distinction can be scientific or legal. The term, hazard, in the environmental context is an inherent property. From a scientific perspective, chemical compound is deemed to be hazardous on the basis of research, e.g., animal testing, epidemiology and/or other studies. Thus a waste may contain hazardous substances, but the waste itself may or may not be hazardous if, for example, the concentrations of the hazardous compound are sufficiently low. Indeed, any waste stream mentioned in this

book can contain “hazardous” waste in varying amounts. From a legal perspective, a specific chemical constituent of any waste stream is deemed to be hazardous based upon expectations that it may cause various kinds of harm, as codified in rules and regulations.

For the most part, hazardous waste has been considered a subset of solid waste and has been distinguished from municipal wastes and nonhazardous industrial wastes. For example, in the United States, the Resource Conservation and Recovery Act (RCRA) [1] has separate subtitles for solid waste, i.e., Subtitle C is for hazardous solid waste and Subtitle D is for nonhazardous solid waste. Incidentally, even

though it is a subset of “solid” waste, a hazardous waste may be of any physical phase, that is, solid, liquid, gas, or mixtures.

The first step of RCRA is to ensure that the wastes are indeed solid or hazardous wastes as defined by the law (see [Table 31.1](#)). If not,

TABLE 31.1 Wastes Excluded From the Definition of Solid Waste Under 40 CFR Section 261, Identification and Listing of Hazardous Waste, Pursuant to the Resource Conservation and Recovery Act Where You Can Find More Information About the Exclusion

Waste Type	40 CFR Subsection
Domestic sewage and mixtures of domestic sewage	§261.4(a)(1)
Point source discharge	§261.4(a)(2)
Irrigation return flow	§261.4(a)(3)
Radioactive waste	§261.4(a)(4)
In situ mining	§261.4(a)(5)
Pulping liquors	§261.4(a)(6)
Spent sulfuric acid	§261.4(a)(7)
Reclamation in enclosed tanks	§261.4(a)(8)
Spent wood preservatives	§261.4(a)(9)
Coke by-product wastes	§261.4(a)(10)
Splash condenser dross residue	§261.4(a)(11)
Hazardous secondary materials from the petroleum refining industry	§261.4(a)(12)
Excluded scrap metal	§261.4(a)(13)
Shredded circuit boards	§261.4(a)(14)
Pulping condensates derived from kraft mill steam strippers	§261.4(a)(15)
Spent materials generated within the primary mineral processing industry from which minerals, acids, cyanide, water, or other values are recovered by mineral processing or by beneficiation	§261.4(a)(17)
Petrochemical recovered oil from an associated organic chemical manufacturing facility	§261.4(a)(18)
Spent caustic solutions from petroleum refining liquid treating processes used as a feedstock to produce cresylic or naphthenic acid	§261.4(a)(19)
Hazardous secondary materials used to make zinc fertilizers	§261.4(a)(20)
Zinc fertilizers made from hazardous wastes or excluded hazardous secondary materials	§261.4(a)(21)
Used cathode ray tubes (CRTs)	§261.4(a)(22)
Hazardous secondary material generated and legitimately reclaimed within the United States or its territories and under the control of the generator	§261.4(a)(23)
Hazardous secondary material that is generated and then transferred to a verified reclamation facility for reclamation is not a solid waste	§261.4(a)(24)
Solvent-contaminated wipes that are sent for cleaning and reuse are not solid wastes from the point of generation	§261.4(a)(26)
Hazardous secondary material that is generated and then transferred to another person for remanufacturing is not a solid waste	§261.4(a)(27)

Source: U.S. Environmental Protection Agency, *Criteria for the Definition of Solid Waste and Solid and Hazardous Waste Exclusions*, 2018. Available from: <https://www.epa.gov/nw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions#tablesv>.

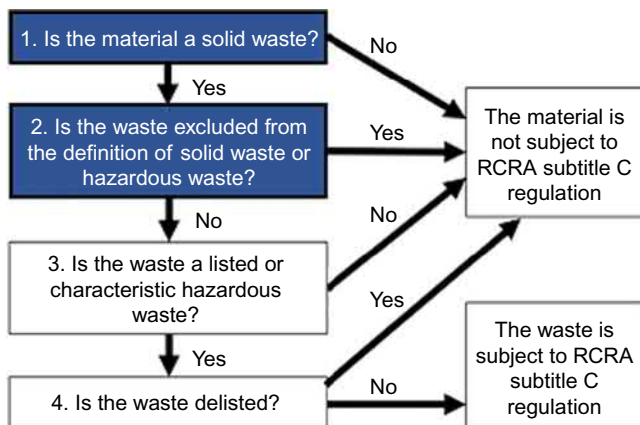


FIG. 31.1 Hazardous waste identification process in the United States. Source: U.S. Environmental Protection Agency, *Criteria for the Definition of Solid Waste and Solid and Hazardous Waste Exclusions*, 2018. Available from: <https://www.epa.gov/lw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions#tablesv>.

other statutes will have primacy, for example, wastewater is controlled under the Clean Water Act [2]. The next step is to identify a hazardous waste (see Fig. 31.1). If the waste is determined to be hazardous, proper handling is required beginning at waste generation through transport to ultimate disposal, that is, the so-called cradle to grave manifest system.

Keeping in mind that the definition of hazardous may also be a legal distinction, some wastes that may otherwise be inherently hazardous are excluded by law. In the United States, for example, this includes several waste streams addressed in separate chapters in this book (see Table 31.2).

Depending on the jurisdiction, a hazardous waste is a solid waste that may pose a substantial present or potential threat to human health and the environment when improperly treated, stored, transported, or otherwise managed. The hazardous attributes of the waste are usually based on its inherent physicochemical properties, including its likelihood to ignite, explode, and react with water (see Table 31.3). A waste's hazardous inherent properties can also be biological, such as the infectious nature of medical wastes, or a chemical compound that has been shown to elicit acute effects, for example, skin irritations and chronic effects, for example, cancer; harm to the endocrine, immune, or nervous system; interference with tissue

development and reproduction; or mutations, birth defects, or other toxic endpoints.

2 MANAGING HAZARDOUS WASTES

Hazardous waste management involves reducing the amount of hazardous substances produced, treating hazardous wastes to reduce their toxicity, and applying sound engineering controls to reduce or eliminate exposures to these wastes. From a chemical engineering perspective, any wastes, but especially hazardous wastes, are produced unintentionally. Facilities that generate the chemicals are attempting to produce substances demanded by the marketplace, but in the process and under the wrong circumstances these substances or their components become hazards. If the same substance were produced intentionally, it would be a *hazardous material*, but not a *hazardous waste*.

Engineers design and operate facilities to prevent, contain, decontaminate, and otherwise treat these wastes before they are released. However, hazardous waste engineering is most often associated with interventions after the wastes have been released. Engineers are frequently called upon to address these wastes once they are released into the environment.

TABLE 31.2 Solid Wastes Which are Excluded From the Definition of Hazardous Waste and the Subsection of 40 CFR Section 261

Solid, But Not Hazardous Wastes	CFR Citation for the Exclusion
Household hazardous waste	§261.4(b)(1)
Agricultural waste	§261.4(b)(2)
Mining overburden	§261.4(b)(3)
Fossil fuel combustion waste (Bevill)	§261.4(b)(4)
Oil, gas, and geothermal wastes (Bentsen amendment)	§261.4(b)(5)
Trivalent chromium wastes	§261.4(b)(6)
Mining and mineral processing wastes (Bevill)	§261.4(b)(7)
Cement Kiln dust (Bevill)	§261.4(b)(8)
Arsenical-treated wood	§261.4(b)(9)
Petroleum contaminated media and debris from underground storage tanks	§261.4(b)(10)
Injected groundwater	§261.4(b)(11)
Spent chlorofluorocarbon refrigerants	§261.4(b)(12)
Used oil filters	§261.4(b)(13)
Used oil distillation bottoms	§261.4(b)(14)
Landfill leachate or gas condensate derived from certain listed wastes	§261.4(b)(15)
Project XL pilot project exclusions	§261.4(b)(17)
Project XL pilot project exclusions	§261.4(b)(18)

Source: U.S. Environmental Protection Agency, *Criteria for the Definition of Solid Waste and Solid and Hazardous Waste Exclusions*, 2018. Available from: <https://www.epa.gov/hw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions#tables>.

A hazard is expressed as the potential of an unacceptable outcome (see Table 31.3). For chemicals, the most important hazard is the potential for disease or death. Epidemiologists refer to these as morbidity and mortality, respectively. The hazards to human health are referred to collectively in the medical and environmental sciences as toxicity. Human toxicology is the study of these health outcomes and their potential causes. Likewise, the study of hazards to ecosystems is known as ecological toxicology or simply ecotoxicology, which is further subdivided by discipline, for example, aquatic toxicology and mammalian toxicology.

2.1 Evaluating Hazards

In the United States, as in many countries, the term hazardous waste is a legal term defined by the regulatory agencies. Under the RCRA hazardous waste regulations, the U.S. Environmental Protection Agency (EPA) is principally responsible for the permitting of hazardous waste treatment, storage, and disposal facilities. The EPA, however, has authorized most states to operate portions or all of their hazardous waste programs. This differs from Subtitle D, nonhazardous wastes. In fact, the U.S. Congress intended that permitting and monitoring of municipal and non-hazardous waste landfills be a state responsibility.

TABLE 31.3 Properties of Hazardous Wastes.

Pictogram	Physical hazard classes	Hazardous properties
	Unstable explosives	HP1 Explosive
	Explosives, divisions 1.1, 1.2, 1.3, 1.4	
	Self-reactive substances and mixtures, types A, B	
	Organic peroxides, types A, B	
	Oxidizing gases, category 1	HP 2 Oxidising
	Oxidizing liquids, categories 1, 2, 3	
	Oxidizing solids, categories 1, 2,	
	Flammable gases, category 1	HP 3 Flammable
	Flammable aerosols, categories 1, 2	
	Flammable liquids, categories 1, 2, 3	
	Flammable solids, categories 1, 2	
	Self-reactive substances and mixtures, types B, C, D, E, F	
	Pyrophoric liquids, category 1	
	Pyrophoric solids, category 1	
	Self-heating substances and mixtures, categories 1, 2	
	Substances and mixtures, which in contact with water, emit flammable gases, categories 1, 2, 3	
	Organic peroxides, types B, C, D, E, F	
No pictogram	Explosive, division 1.5	HP 15
	Explosive, division 1.6	Not applicable
	Flammable gas, category 2	HP 3 Flammable
	Self-reactive substances and mixtures, type G	Not applicable
	Organic peroxides, type G	Not applicable
	Compressed gases	No hazardous property
	Liquefied gases	
	Refrigerated liquefied gases	
	Dissolved gases	
	Skin corrosion, category 1A	HP 4 Irritant HP 8 Corrosive
	Skin corrosion, categories 1B and 1C	HP 8 Corrosive
	Serious eye damage, category 1	HP 4 Irritant
	Corrosive to metals	Not applicable

Continued

FOR REFERENCE PURPOSES ONLY

TABLE 31.3 Properties of Hazardous Wastes.—cont'd

Pictogram	Physical hazard classes	Hazardous properties
	Acute toxicity (oral, dermal, inhalation), categories 1, 2, 3	HP6 Acute Toxicity
	Respiratory sensitization, category 1	HP 13 Sensitising
	Germ cell mutagenicity, categories 1A, 1B, 2	HP 11 Mutagenic
	Carcinogenicity, categories 1A, 1B, 2	HP 7 Carcinogenic
	Reproductive toxicity, categories 1A, 1B, 2	HP 10 Toxic for reproduction
	Specific target organ toxicity following single exposure, categories 1, 2	HP 5 Specific Target Organ Toxicity / Aspiration Toxicity
	Specific target organ toxicity following repeated exposure, categories 1, 2	
	Aspiration hazard, categories 1, 2	
	Acute toxicity (oral, dermal, inhalation), category 4	HP 6 Acute Toxicity
	Skin irritation, categories 2, 3	HP 4 Irritant
	Eye irritation, category 2	
	Skin sensitization, category 1	HP 13 Sensitising
	Specific target organ toxicity following single exposure, cat. 3 • Respiratory tract irritation • Narcotic effects	HP 5 Specific Target Organ Toxicity / Aspiration Toxicity
No pictogram	Acute toxicity (oral, dermal, inhalation), category 5	Not applicable
	Reproductive toxicity – effects on or via lactation	Not applicable
Not subject to chemical labelling requirements	Not applicable	HP 9 Infectious
	Hazardous to the aquatic environment – acute aquatic hazard, category 1	HP 14 Ecotoxic
	Hazardous to the aquatic environment – long-term aquatic hazard, categories 1, 2	
	Hazardous to the ozone layer	HP 14 Ecotoxic
No pictogram	Hazardous to the aquatic environment – acute aquatic hazard, categories 2, 3.	HP 14 Ecotoxic
	Hazardous to the aquatic environment – long-term aquatic hazard, categories 3, 4	HP 14 Ecotoxic

From United Kingdom Environmental Agency, et al., *Waste Classification: Guidance on the Classification and Assessment of Waste (1st Edition v1.1)*, Technical Guidance WM3, May 2018, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/719394/Waste-classification-technical-guidance-WM3.pdf.

The EPA has developed standard approaches and set criteria to determine if substances exhibit hazardous characteristics [3]. Because RCRA defines a hazardous waste as a waste that presents a threat to human health and the environment when it is improperly managed, the government identified a set of assumptions that would allow for a waste to be disposed if it is not subject to the controls mandated by Subtitle C of RCRA. This mismanagement scenario was designed to simulate a plausible worst case.

Under a worst-case scenario, a potentially hazardous waste is assumed to be disposed along with municipal solid waste in a landfill with actively decomposing substances overlying an aquifer. Hopefully, few wastes would be managed in this manner but a dependable set of assumptions are needed to ensure that the hazardous waste definition was implemented. The Hazardous and Solid Waste Amendments of 1984 (HSWA) established the Toxicity Characteristic Leaching Procedure (TCLP) to provide replicable results for contaminants commonly found in hazardous waste sites (see Table 31.4). The specific medium or substrate used in the test is dictated by the alkalinity of the waste. The liquid extracted from the waste is analyzed for the 39 listed toxic constituents and the concentration of each contaminant is

TABLE 31.4 Toxicity Characteristic Chemical Constituent Regulatory Levels for 39 Hazardous Chemicals

Contaminant	Regulatory Level (mgL ⁻¹)
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0

Endrin	0.02
Lindane	0.4
Methoxychlor	10.0
Toxaphene	0.5
2,4-D	10.0
2,4,5 TP (Silvex)	1.0
Benzene	0.5
Carbon tetrachloride	0.5
Chlordane	0.03
Chlorobenzene	100.0
Chloroform	6.0
<i>o</i> -Cresol	200.0
<i>m</i> -Cresol	200.0
<i>p</i> -Cresol	200.0
Cresol	200.0
1,4-Dichlorobenzene	7.5
1,2-Dichloroethane	0.5
1,1-Dichloroethylene	0.7
2,4-Dinitrotoluene	0.13
Heptachlor (and its hydroxide)	0.008
Hexachloroethane	3.0
Hexachlorobutadiene	0.5
Hexachloroethane	3.0
Methyl ethyl ketone	200.0
Nitrobenzene	2.0
Pentachlorophenol	100.0
Pyridine	5.0
Tetrachloroethylene	0.7
Trichloroethylene	0.5
2,4,5-Trichlorophenol	400.0
2,4,6-Trichlorophenol	2.0
Vinyl chloride	0.2

Source: Resource Conservation and Recovery Act of 1976, 40 CFR 261 and 262.11, 1976.

compared to the TCLP standards specific to each contaminant [4].

Hazards other than toxicity are also important and regulated accordingly. These include threats to public and personal safety, which may result from a substance's potential to ignite, its corrosiveness, flammability, or explosiveness. A substance may be hazardous to public welfare if it damages property values or physical materials; for example, expressed as its corrosiveness or acidity. The hazard may also relate to environmental quality, such as an ecosystem stress indicated by diminished productivity and biodiversity, loss of important habitats, and decreases in the size of the population of sensitive species. The hazard may be inherent to the substance. But more than likely, the hazard depends upon the situation and conditions where the exposure may occur. The substance is most hazardous when a number of conditions exist simultaneously, such as the hazard to firefighters using water in the presence of oxidizers.

Since 1980, specific methods for testing of hazards are delineated in the EPA publication SW-846, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, which is a compendium of analytical and sampling methods that comply with the RCRA regulations. The SW-846 provides guidance, although not necessarily a legal requirement, when conducting RCRA-related sampling and analysis requirements. This guidance is updated and revised as new information become available. It is currently in its third edition as a fully integrated 3500 page manual [3].

2.2 Waste Management Hierarchy

A typical sequence for managing hazardous wastes involves source reduction, recycling, treatment, and disposal [5]. The waste generator is encouraged to begin at the top of the hierarchy and proceed downward, if necessary (obviously, if the waste is eliminated, there is no further need to follow the sequence). In the United States, the term pollution prevention is often

preferred to source reduction, and waste minimization is used as an umbrella term for strategies and technologies that use source reduction and recycling techniques (Fig. 31.2).

2.2.1 Source Reduction

Reducing the amount or severity of a hazardous can be achieved via process modifications, feedstock substitutions, improvements in feedstock purity, changes in housekeeping and management practice, increases in the efficiency of equipment, and recycling within a process [6]. In the United States, there is a requirement in the federal environmental regulations that all large hazardous waste generators must have a program at their facility to encourage source reduction and recycling. Other countries, such as Austria, Germany, and Denmark, have initiated direct subsidies to encourage preferable waste management options.

2.2.2 Recycling

The use or reuse of hazardous waste as an effective substitute for a commercial product or as an ingredient or feedstock in an industrial process can not only be advantageous from a public health and environmental standpoint, but also from a financial perspective. Recycling includes the reclamation of useful constituent fractions within a waste material or the removal of contaminants from a waste to allow it to be reused.

2.2.3 Disposal and Treatment

Hazardous waste disposal consists of the discharge, deposit, injection, dumping, spilling, leaking, or placing of hazardous waste into or on any land or body of water so that the waste or any constituents may enter the air or be discharged into any waters, including groundwater.

The portion of the hazardous waste that cannot be eliminated or recycled must undergo a method, technique, or process that changes the substance's physical, chemical, or biological character to neutralize it; to recover energy or material resources from the waste; or to render

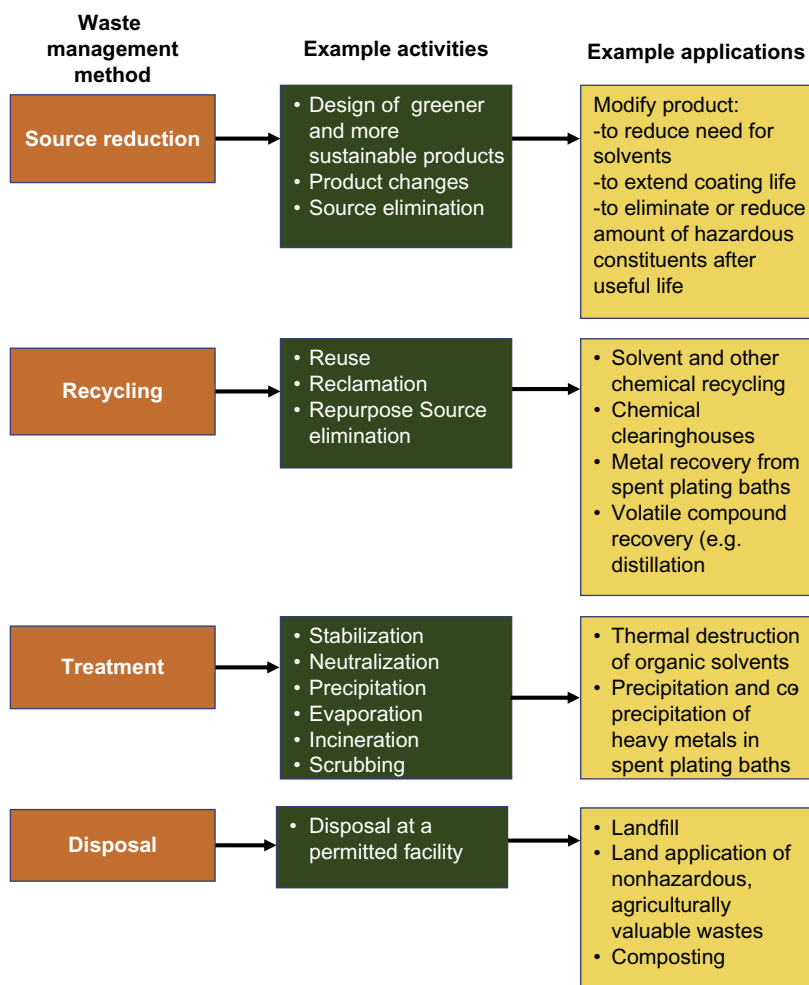


FIG. 31.2 Flowchart for management of waste: reduction from manufacture, use, treatment, and disposal. Data from U.S. Environmental Protection Agency, *Facility Pollution Prevention Guide*, EPA/600/R-92/088, 1992; D.A. Vallero, *Hazardous wastes*, in: *Encyclopedia of Science and Technology*, ed., AccessScience, McGraw-Hill Education, New York, NY, 2017.

the waste nonhazardous, less hazardous, safer to manage, amenable for recovery, amenable for storage, or reduced in volume.

2.3 Hazard Incident Response

This chapter stresses the environmental hazards, but other paradigms exist. For example, in the United States, the Occupational Health

and Safety Administration (OSHA) is interested in protecting workers from exposure to hazards at waste sites. This calls for an incident response model that consists of five components [7]:

1. Recognition
2. Evaluation
3. Information
4. Safety
5. Control

Before entering a potentially dangerous situation at a waste site, one needs to recognize potential hazards, including the physical, chemical, and biological hazards mentioned previously. However, this is not enough for safe entry. An evaluation of the site depends on sound information. This can be drawn from current and previous site investigations; interviews with suppliers, customers, employees; and scientifically sound sampling and monitoring before, during, and after any incident response. Controls include containment, suppression, and treatment and depending on the severity of a hazard, for example, immediate evacuation from a potentially explosive situation, or shutoff of a contaminated drinking water supply.

This process may involve either physical or health hazards. Physical hazards include reactivity, fire, explosion, corrosivity, and radioactivity. Health hazards include various types of effects, including acute effects like poisoning to chronic effects such as cancer or neurotoxicity.

Anyone involved in any emergency or incident response must be properly trained to recognize these hazards. Thus the EPA and OSHA require completion of an intensive course in hazardous waste operations and emergency response. Employers must provide this training and must ensure that workers be recertified annually.

3 TREATMENT TECHNOLOGIES

Waste treatment technologies include physical treatment, chemical treatment, biological treatment, incineration, and solidification or stabilization treatment. These processes recycle and reuse waste materials, reduce the volume and toxicity of a waste stream, or produce a final residual material that is suitable for disposal.

The selection of the most effective technology depends upon the characteristics of the wastes being treated [8]. Likewise, the characteristics of the media in need of treatment determine the

performance of any contaminant treatment or control. For example, if the waste is found in sediment, sludge, slurries, and soil, these media's characteristics will influence the efficacy of treatment technologies including particle size, solids content, and high contaminant concentration (see Table 31.5). The U.S. Environmental Protection Agency's Remediation Guidance Document [8] provides details on several of the treatment technologies discussed in this chapter.

As is common in most environmental situations, particle size is an important limiting characteristic for applying treatment technologies to porous media. Most treatment technologies work well on sandy soils and sediments. The presence of fine-grained material reduces the effectiveness of treatment system emission controls because it increases particulate generation during thermal drying; it is more difficult to dewater, and it has a greater attraction for the contaminants; especially fine-grained clays. Clayey sediments that are cohesive also present materials handling problems in most processing systems.

Solids content generally range from high (30%–60% solids by weight) to low (10%–30% solids by weight). Treatment of slurries is better at lower solids contents, but this can be achieved for high solids contents by adding water at the time of processing. It is more difficult to change from a lower to a higher solids content, but evaporative and dewatering approaches, such as those used for municipal sludges, may be used. Also, thermal and dehalogenation processes are decreasingly efficient as the solids content is reduced. More water means increased chemical costs and an increased need for wastewater treatment.

Chemical composition of the wastes must also be considered in the treatment of hazardous wastes. Elevated levels of organic compounds or heavy metals in high concentrations may require special safeguards. Organic matter can be a bonus, given that higher total organic carbon (TOC) content favors incineration and

TABLE 31.5 Effect of Particle Size, Solids Content, and Extent of Contamination on Decontamination Efficiencies

Treatment Technology	Predominant Particle Size			Solids Content		High Contaminant Concentration	
	Sand	Silt	Clay	High (Slurry)	Low (In Situ)	Organic Compounds	Metals
Conventional incineration	N	X	X	F	X	F	X
Innovative incineration	N	X	X	F	X	F	F
Pyrolysis	N	N	N	F	X	F	F
Vitrification	F	X	X	F	X	F	F
Supercritical Water oxidation	X	F	F	X	F	F	X
Wet air oxidation	X	F	F	X	F	F	X
Thermal desorption	F	X	X	F	X	F	N
Immobilization	F	X	X	F	X	X	N
Solvent extraction	F	F	X	F	X	X	N
Soil washing	F	F	X	N	F	N	N
Dechlorination	U	U	U	F	X	X	N
Oxidation	F	X	X	N	F	X	X
Bioslurry process	N	F	N	N	F	X	X
Composting	F	N	X	F	X	F	X
Contained treatment facility	F	N	X	F	X	X	X

Note: F: sediment characteristic favorable to the effectiveness of the process.

N: sediment characteristic has no significant effect on process performance.

U: effect of sediment characteristic on process is unknown.

X: sediment characteristic may impede process performance or increase cost.

Source: D. Averett, Chapter 7: treatment technologies, in: *Assessment and Remediation of Contaminated Sediments (ARCS) Program: Remediation Guidance Document*, G.L.N.P.O. U.S. Environmental Protection Agency, ed., Chicago, Illinois, 1994.

oxidation processes. The TOC can be the contaminant of concern or any organic, since they are combustibles with caloric value. Conversely, higher metal concentrations may make a technology less favorable by increasing contaminant mobility of certain metal species following processing.

Numerous other factors affect the selection of a hazardous waste treatment technology (Table 31.6). For example, vitrification and supercritical water oxidation have only been used for relatively small projects and have not

been proven for use in full-scale sediment projects. Regulatory compliance and community perception are always a part of decisions regarding an incineration system. Land use considerations, such as the area needed, are commonly confronted in solidification and solid-phase bioremediation projects, as well as in sludge farming and land application. Disposing of ash and other residues following treatment must be part of any process. Treating water effluent and air emissions must be part of the decontamination decision-making process.

TABLE 31.6 Factors for Selecting Decontamination and Treatment Approaches

Treatment Technology	Implementability at Full Scale	Regulatory Compliance	Community Acceptance	Land Requirements	Residuals Disposal	Wastewater Treatment	Air Emissions Control
Conventional incineration		✓	✓				✓
Innovative incineration		✓	✓				✓
Pyrolysis		✓					✓
Vitrification	✓	✓					✓
Supercritical water oxidation	✓						
Wet air oxidation							
Thermal desorption					✓	✓	✓
Immobilization				✓			✓
Solvent extraction					✓	✓	
Soil washing					✓	✓	
Dechlorination							✓
Oxidation	✓						
Bioslurry process	✓						✓
Composting				✓			✓
Contained treatment facility				✓		✓	✓

Note: ✓: the factor is critical in the evaluation of the technology.

Source: D. Averett, Chapter 7: Treatment technologies, in: *Assessment and Remediation of Contaminated Sediments (ARCS) Program: Remediation Guidance Document*, G.L.N.P.O. U.S. Environmental Protection Agency, ed., Chicago, Illinois, 1994.

Processes are available to separate components of a waste stream or change the physical form of the waste without altering the chemical structure of the constituent materials. Physical treatment techniques are often used to separate the materials within the waste stream so that they can be reused or detoxified by chemical or biological treatment or destroyed by high-temperature incineration. These processes are very useful for separating hazardous materials from an otherwise nonhazardous waste stream so that they may be treated in a more

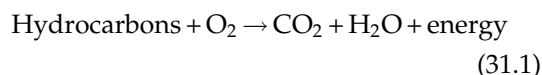
concentrated form, separating various hazardous components for different treatment processes, and preparing a waste stream for ultimate destruction in a biological or thermal treatment process.

Most integrated waste treatment systems use physical treatment regardless of the nature of the waste materials or the ultimate technologies used for treatment or destruction. The processes commonly include screening, sedimentation, flotation, filtration, centrifugation, dialysis, membrane separations, ultrafiltration,

distillation, solvent extraction, evaporation, and adsorption.

3.1 Thermal Destruction

The organic portion of wastes has heat value. This means that this portion of any waste can be completely destroyed using principles based on thermodynamics, ultimately yielding carbon dioxide and water:



Complete combustion may also result in the production of molecular nitrogen (N_2) when nitrogen-containing organics are burned, such as in the combustion of methylamine. Incomplete combustion can produce a variety of compounds. Some are more toxic than the original compounds being oxidized, such as polycyclic aromatic hydrocarbons (PAHs), dioxins, furans, and carbon monoxide.

Thermal destruction begins by mixing of wastes with oxygen, sometimes in the presence of an external energy source, and within several seconds the by-products of gaseous carbon dioxide and water are produced and exit the top of the reaction vessel, while a solid ash is produced that exits the bottom of the reaction vessel. Energy may also be produced during the reaction and the heat may be recovered.

If the wastes contain other chemical constituents, particularly chlorine and/or heavy metals, the situation becomes complex. For such wastes, the potential exists for destroying the initial contaminant as well as exacerbating the problem by generating hazardous off-gases containing chlorinated hydrocarbons or ashes containing heavy metals. For example, the improper incineration of certain chlorinated hydrocarbons can lead to the formation of the highly toxic chlorinated dioxins, furans, and hexachlorobenzene.

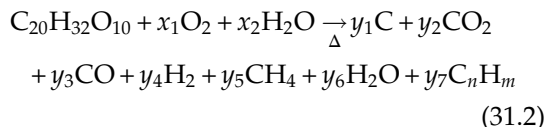
The benefits of thermal systems include:

- (1) the potential for energy recovery;
- (2) volume reduction of the contaminant;
- (3) detoxification as selected molecules are reformulated;
- (4) the basic scientific principles, engineering designs, and technologies are well understood from a wide range of other applications, including electric generation and municipal solid waste incineration;
- (5) application to most organic contaminants which compose a large percentage of the total contaminants generated worldwide;
- (6) the possibility to scale the technologies to handle a single gallon per pound (liter per kilogram) of waste or millions of gallons per pound (megaliter per kilogram) of waste; and,
- (7) the land areas requirements are small relative to other hazardous waste management facilities such as landfills.

The common drawbacks of thermal destruction technologies include:

- (1) the capital intensity of equipment, particularly the refractory material lining the inside walls of each combustion chamber which must be replaced as cracks form whenever a combustion system is cooled and heated;
- (2) the need for very skilled operators and is costlier to operate when fuel must be added to the system;
- (3) the buildup of ash that will need to be handled, often as a new hazardous waste, which is particularly costly and difficult if heavy metals and/or chlorinated compounds are present; and,
- (4) the emission of air pollutants (particularly products of incomplete combustion, so-called PICs, and heavy metals) which must be monitored for chemical constituents and controlled.

In general, the same reaction applies to most thermal processes of gasification, pyrolysis, hydrolysis, and combustion:



The coefficients x and y balance the compounds on either side of the equation. In many thermal reactions, C_nH_m includes the hydrocarbons,

C_2H_2 , C_2H_4 , C_2H_6 , C_3H_8 , C_4H_{10} , C_5H_{12} , and benzene, C_6H_6 . Of all of the thermal processes, incineration is the most common process for destroying organic contaminants in industrial wastes. Incineration simply is heating wastes in the presence of oxygen to oxidize organic compounds (both toxic and nontoxic). The principal incineration steps are shown in Fig. 31.3.

Incineration is the most common thermal treatment process for organic contaminants in industrial and municipal wastes. Incineration

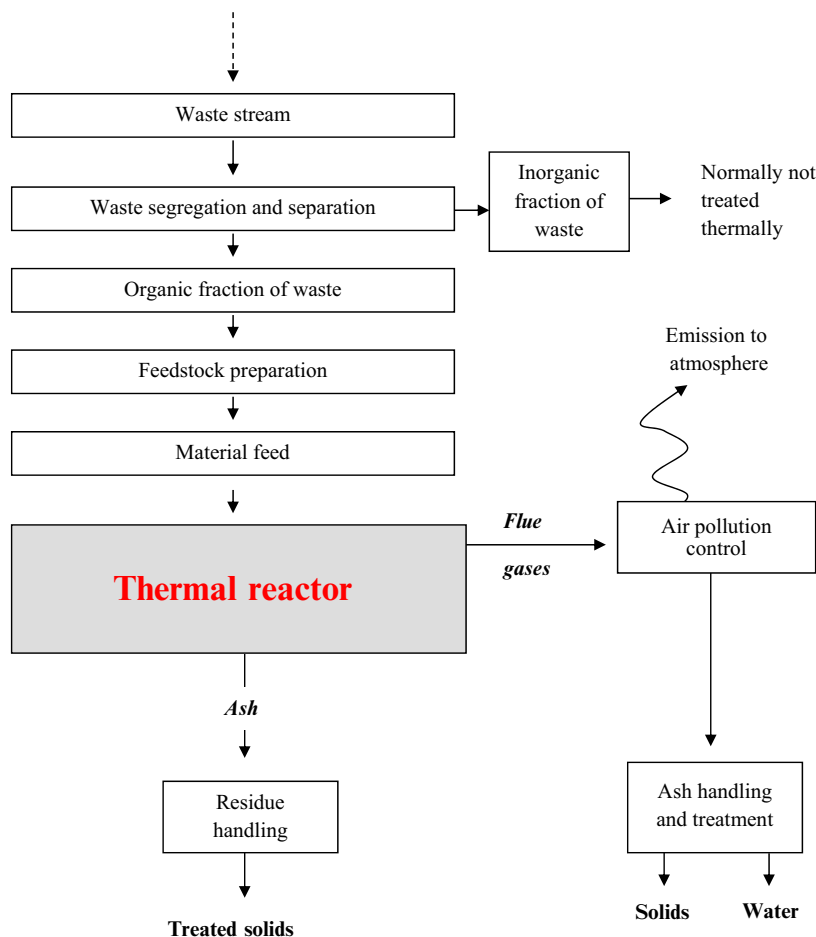
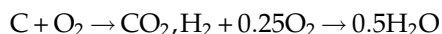


FIG. 31.3 Steps in the thermal destruction of wastes. Adapted from D. Averett, Chapter 7: treatment technologies, in: *Assessment and Remediation of Contaminated Sediments (ARCS) Program: Remediation Guidance Document*, G.L.N.P.O. U.S. Environmental Protection Agency, ed., Chicago, Illinois, 1994.

simply is heating wastes in the presence of oxygen to oxidize organic compounds. The principal reactions from test burns for commonly incinerated compounds are provided in Table 31.7. Note that these generally follow the stoichiometry of Eq. (31.2), but vary by the chemical composition of the fuel.

Wood is considered to have the composition of $C_{6.9}H_{10.6}O_{3.5}$. Therefore the combustion consists simply of the oxidation of carbon and hydrogen:



There are a number of stages in the incineration process where new compounds may need to be addressed. Ash and other residues may contain high levels of metals, at least higher than the original feed. The flue gases are likely to include both organic and inorganic compounds resulting from temperature-induced volatilization or newly transformed products of incomplete combustion (PICs) with higher vapor pressures than the original contaminants.

3.1.1 Types of Thermal Units

Although they are often call “combustion” units, they are more accurately “thermal destruction” units, since they may or may not have excess oxygen. Thermal units range in size;

characteristics; and varying time, temperature, and turbulence, the “3T’s” to achieve optimal destruction of harmful constituents and to reduce the volume of wastes. If complete combustion is the goal, excess oxygen is also often needed, for example, the oxidative processes predominate. The excess oxygen helps to pyrolytic processes that can produce toxic by-products. A well-mixed chamber, that is, optimal turbulence, is needed to avoid regions of oxygen deficit. Generally, oxygen should be present at 50%–100% higher concentration than is theoretically required to decompose the waste.

Many of the challenges of municipal solid waste (MSW) burning apply to hazardous waste thermal treatment. Indeed, MSW can be more challenging given the variability of waste characteristics compared, for example, to a single hazardous waste type, albeit the latter likely has much higher overall toxicity. Mass-burn facilities are the most common type of thermal treatment in the United States. This approach requires little or no sorting of waste for entry into the combustion chamber. However, some municipalities using mass-burn separate the waste to save recyclable products. Excess air promotes mixing and turbulence to ensure that air can reach all parts of the waste. This is needed for mixed wastes that have variable

TABLE 31.7 Balanced combustion reactions for selected organic compounds [1]

Chlorobenzene	$C_6H_5Cl + 7O_2 \rightarrow 6CO_2 + HCl + 2H_2O$
Tetrachloroethene (TCE)	$C_2Cl_4 + O_2 + 2H_2O \rightarrow 2CO_2 + HCl$
Hexachloroethane (HCE)	$C_2Cl_6 + \frac{1}{2}O_2 + 3H_2O \rightarrow 2O_2 + 6HCl$
Postchlorinated polyvinyl chloride (CPVC)	$C_4H_5Cl_3 + 4.5O_2 \rightarrow 4CO_2 + 3HCl + H_2O$
Natural gas fuel (methane)	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
PTEE Teflon	$C_2F_4 + O_2 \rightarrow CO_2 + 4HF$
Butyl rubber	$C_9H_{16} + 13O_2 \rightarrow 9CO_2 + 8H_2O$
Polyethylene	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$

Note: TCE, tetrachloroethene; HCE, hexachloroethane; CPVC, postchlorinated polyvinyl chloride; PFTE, polytetrafluoroethylene.

Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999.

characteristics, for example, MSW. Most mass-burn facilities burn MSW on a sloping, moving grate that vibrates or otherwise moves to agitate the waste and mix it with air. Modular systems burning unprocessed, mixed wastes are usually much smaller and portable than mass-burn systems. Refuse-derived fuel systems use mechanical methods to shred incoming wastes, separate out noncombustible materials, and produce a combustible mixture that is suitable as a fuel in a dedicated furnace or as a supplemental fuel in a conventional boiler system [9].

General categories of thermal destruction are available. The prototypes include: (1) rotary kiln, (2) multiple hearth, (3) liquid injection, (4) fluidized bed, (5) moving grate, and (6) multiple chamber.

ROTARY KILN

The combustion chamber in a rotary kiln incinerator (see Fig. 31.4) is a heated rotating cylinder mounted at an angle with possible baffles added to the inner face to provide the turbulence

necessary for the target 3 T's. Engineering design options flow from the results of laboratory testing of a specific contaminant, including (1) angle of the drum, (2) diameter and length of the drum, (3) presence and location of the baffles, (4) rotational speed of the drum, and (5) use of added fuel to increase the temperature of the combustion chamber as the specific contaminant requires. The liquid, sludge, or solid hazardous waste is input into the upper end of the rotating cylinder, rotates with the cylinder-baffle system, and falls with gravity to the lower end of the cylinder. The heated upward moving off-gases are collected, monitored for chemical constituents, and subsequently treated as appropriate prior to release, while the ash falls with gravity to be collected, monitored for chemical constituents, and treated as needed before ultimate disposal. The newer rotary kiln systems [2] consist of a primary combustion chamber, a transition volume, and a fired afterburner chamber. After exiting the afterburner, the flue gas is passed through a quench section followed by a primary APCS.

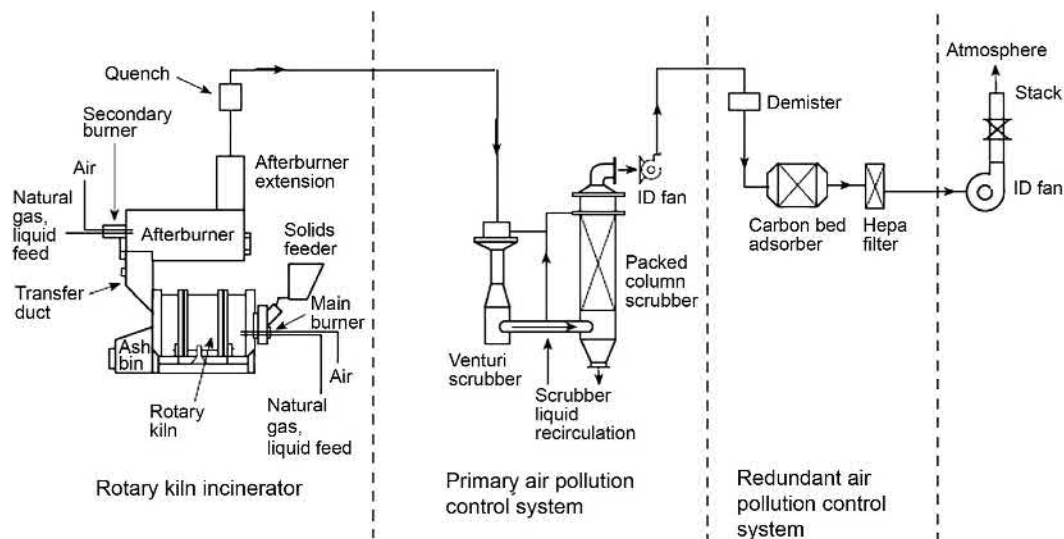


FIG. 31.4 Rotary kiln system. Adapted from J. Lee, D. Fournier, C. King, S. Venkatesh, C. Goldman, *Evaluation of Rotary Kiln Incinerator Operation at Low-to-Moderate Temperature Conditions*, vol. 1, Technical Results, 1996.

The primary air pollution control system (APCS) can be a venture scrubber followed by a packed column scrubber. Downstream of the primary APCS, a backup secondary APCS, with a demister, an activated-carbon adsorber, and a high-efficiency particulate air (HEPA) filter can collect contaminants not destroyed by the incineration.

The rotary kiln can be used to incinerate most organic contaminants, it is well suited for solids and sludges, and in special cases liquids and gases can be injected through auxiliary nozzles in the side of the combustion chamber. Operating temperatures generally vary from 800°C to 1650°C. Engineers use laboratory experiments to design residence times of seconds for gases and minutes or possibly hours for the incineration of solid material.

MULTIPLE HEARTH

Multiple hearths (see Fig. 31.5) usually are used for contaminants in solid or sludge form is fed slowly through the top vertically stacked hearth; in special configurations hazardous gases and liquids can be injected through side nozzles. They were first used to burn municipal wastewater treatment biosolids (i.e., sludges), relying on gravity and scrapers working the upper edges of each hearth to transport the waste through holes from upper hotter hearths to lower cooler hearths. Heated upward moving off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release; the falling ash is collected, monitored for chemical constituents, and subsequently treated prior to ultimate disposal.

Numerous waste types with varying organic content can be incinerated using a multiple hearth configuration. Operating temperatures generally vary from 300°C to 980°C. These systems are designed with residence times of seconds if gases are fed into the chambers to several hours if solid materials are placed on the top hearth and allowed to eventually drop to the bottom hearth exiting as ash.

LIQUID INJECTION

Nozzles mount horizontally and/or vertical spray liquid hazardous wastes into liquid injection incinerators. That is, the wastes are atomized to match the waste being handled with the combustion chamber as determined in laboratory testing. The application obviously is limited to liquids that do not clog these nozzles, though some success has been experienced with hazardous waste slurries. Operating temperatures generally vary from 650°C to 1650°C (1200°F to 3000°F). Liquid injection systems (see Fig. 31.6) are designed with residence times of fractions of seconds. The upwardly moving off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release to the lower troposphere of the atmosphere.

FLUIDIZED BED

Contaminated feedstock is injected under pressure into a heated bed of agitated inert granular particles, usually sand, as the heat is transferred from the particles to the waste, and the combustion process proceeds as shown in Fig. 31.7. External heat is applied to the bed prior to the injection of the waste. Heat is also continually applied throughout the combustion operation as the situation dictates. Heated air is forced into the bottom of the particle bed and the particles become suspended among themselves during this continuous fluidizing process. The openings created within the bed permit the introduction and transport of the waste into and through the bed. The process enables the contaminant to come into contact with particles that maintain their heat better than, for example, the gases inside a rotary kiln. The heat maintained in the particles increases the time the contaminant is in contact with a heated element and thus the combustion process could become more complete with fewer harmful by-products. Off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to

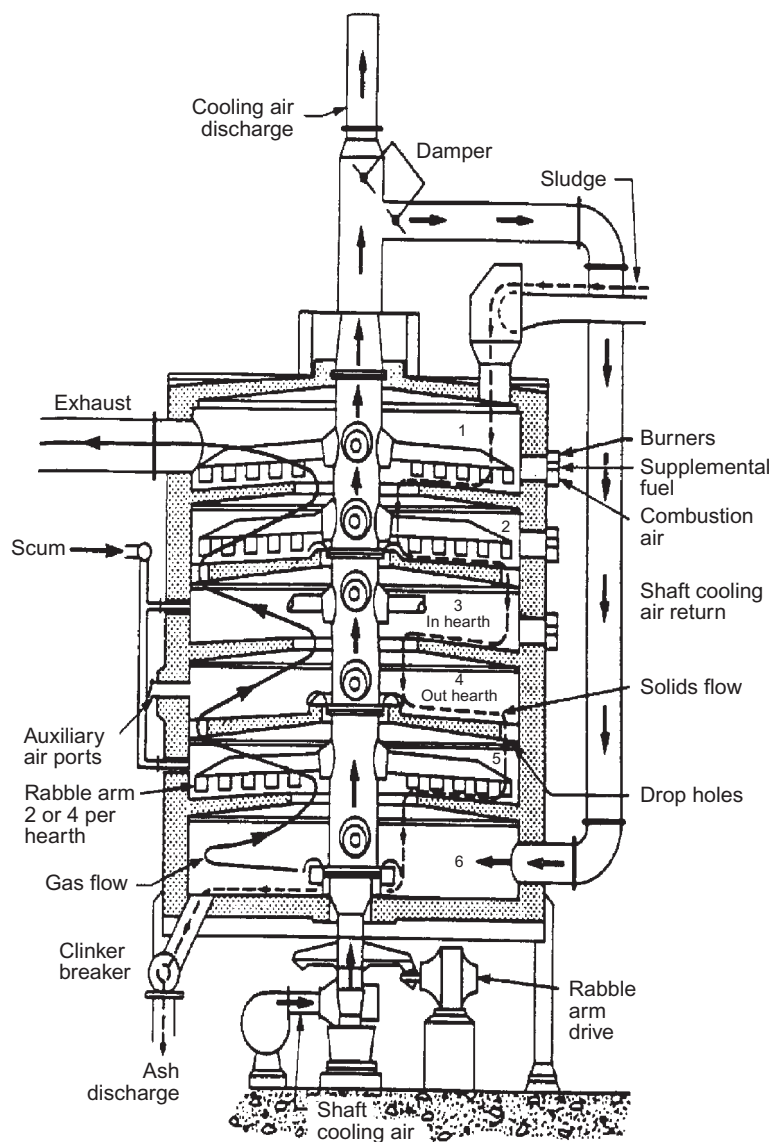


FIG. 31.5 Multiple hearth incineration system. Source: E.P.A. U.S., *Locating and Estimating Air Emissions From Sources of Benzene*, Research Triangle Park, NC, 1998.

release, and the falling ash is collected, monitored for chemical constituents, and subsequently treated prior to ultimate disposal.

Most organic wastes can be incinerated in a fluidized bed, while the system is best suited for liquids. Operating temperatures generally

vary from 750°C to 900°C. Liquid injection systems are designed with residence times of fractions of seconds as off-gases the upward moving off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release to the lower troposphere.

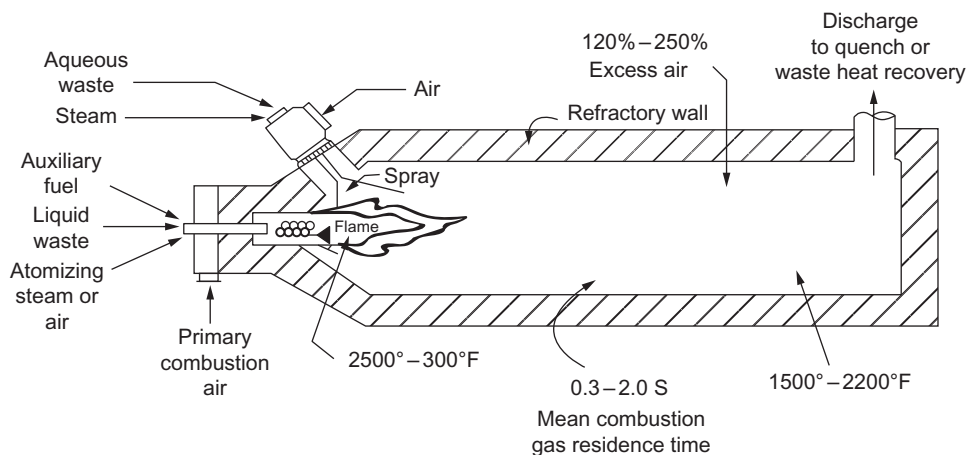


FIG. 31.6 Prototype of liquid injection system. Source: E.P.A. U.S., *Locating and Estimating Air Emissions From Sources of Benzene*, Research Triangle Park, NC, 1998.

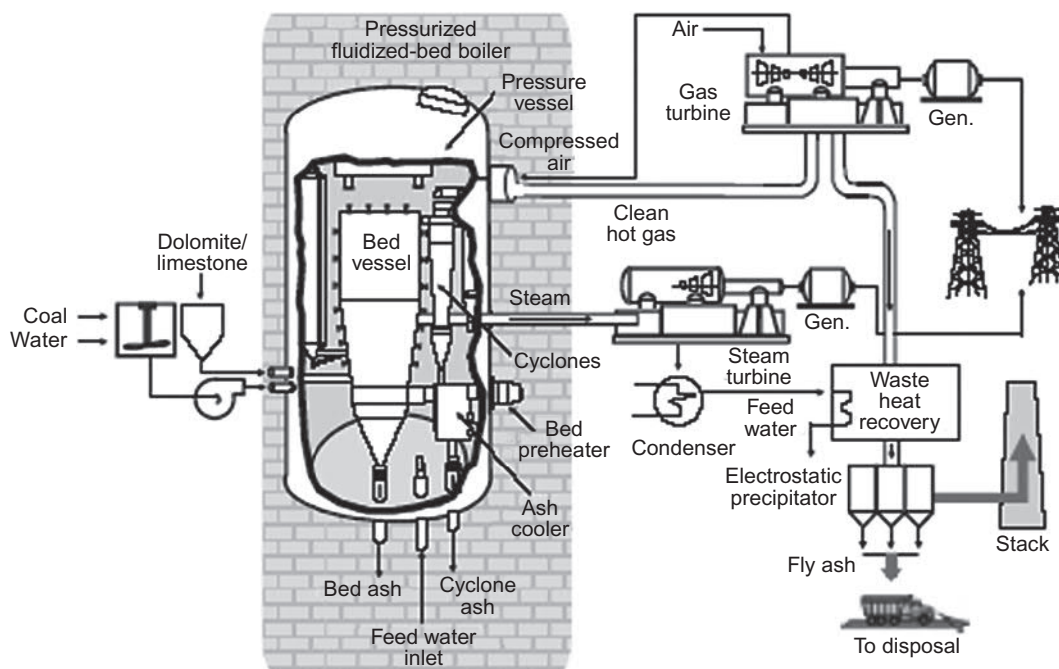


FIG. 31.7 Pressurized fluidized bed system. Source: DOE/FE-0398, TIDD PFBC Demonstration Project, 1999.

MOVING HEARTH OR MOVING GRATE SYSTEM

There can be advantage to loading wastes and removing ash continuously. This setup offers more control compared to agitation, which is an advantage when for biologicals, for example, clinical and medical, wastes, that produce a high percentage of ash. They are also less expensive to build and usually generate less PM emissions. There have been problems with some early designs that use moving grates [9].

MULTIPLE CHAMBERS

Wastes are first vaporized on a grate in the ignition chamber of a multiple chamber system. The gases created in this ignition chamber travel through baffles to a secondary chamber where the actual combustion process takes place. Often the secondary chamber is located above the ignition chamber to promote natural advection of the hot gases through the system. Heat may be added to the system in either the ignition chamber or the secondary chamber as required for specific burns.

The application of multiple chamber incinerators is mainly restricted to solid wastes, wherein the waste enters the ignition chamber through an opened charging door in batch, not continuous, loading. Combustion temperatures are typically near 540°C for most applications. Multiple chamber units normally are designed with residence times of minutes to hours for solid hazardous wastes as off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release to the lower troposphere. At the end of each burn period the system must be cooled so that the ash can be removed prior to monitoring for chemical constituents and subsequent treatment prior to ultimate disposal.

Incineration alone does not “destroy” some wastes. Some elements, like the metals, are actually concentrated in the ash and other incineration residues. Thermal treatment changes the oxidation state (valence) of the metals. In fact, incineration can actually replace on problem with

another, such as increasing the potential movement of metals via oxidation, allowing the metals to migrate into the environment. Conversely, processes like slagging (operating at sufficiently high temperatures to melt and remove incombustible materials) or vitrification (producing non-leachable, basalt-like residue) can substantially reduce the mobility of many metals.

3.1.2 Thermal Optimization

The chemical and physical characteristics of the waste determine how a waste is to be thermally treated. The key is to make the waste less harmful. This often means making a waste less mobile and less toxic. For example, Australia [10] has identified the suitability of wastes to various thermal treatment process according to the waste’s properties (see Table 31.8).

LEACHABILITY TESTING PRIOR TO TREATMENT

The measure of the ease with which compounds in the waste can move into the accessible environment is known as leachability. The increased leachability of metals would be problematic if the ash and other residues are to be buried in landfills or stored in piles. The leachability of metals is generally measured using the toxicity characteristic leaching procedure (TCLP) test, discussed earlier. Incinerator ash that fails the TCLP must be disposed of in a waste facility approved for hazardous wastes. Enhanced leachability would be advantageous only if the residues are engineered to undergo an additional treatment step of metals. Again, the engineer must see incineration of but one component within a systematic approach for any contaminant treatment process.

New compounds can be created at various steps as the contaminant moves through the incineration process. As mentioned, ash and other residues may contain high levels of metals, at least higher than the original feed. The flue gases are likely to include both organic and inorganic compounds that have been released as a result of temperature-induced volatilization

TABLE 31.8 Applicability of Waste Destruction by Physical and Chemical Properties

Waste Type	Cement Kiln	Rotary Kiln	Multiple Chamber	Multihearth	Fluidized Bed	Liquid Injection
Solids						
Granular, homogeneous		X	X	X	X	
Irregular, bulky (e.g., pallets)		X	X			
Low melting point compounds (e.g., tars)	X	X	X	X	X	
Organics with fusible ash		X	X			
Gases						
Organic gases and vapors		X	X			X
Liquids						
Aqueous phase, contaminated with organics	X	X	X			X
Organic liquids, including halogenated	X	X	X		X	X
Solids/liquids						
Waste with halogens	X	X	X		X	X
Aqueous/organic sludges	X	X	X	X	X	X

Adapted from *Clear The Air, Incineration Policy in Australia*, 2011. Available from: <http://news.cleartheair.org.hk/?p=2040>.

and/or newly transformed products of incomplete combustion with higher vapor pressures than the original contaminants.

Based on these underlying principles, seven general incineration guidelines can be highlighted:

1. liquid phase, nearly pure organic contaminants are best candidates for combustion;
2. halogen-containing organic materials deserve special consideration if in fact they are to be incinerated at all; that is, special materials used in the construction of the incinerator, long (many seconds) of combustion time, high temperatures ($>1600^{\circ}\text{C}$), with continuous mixing if the contaminant is in the solid or sludge form;
3. Feedstock containing heavy metals generally should not be incinerated;
4. Sulfur-containing organic material will emit sulfur oxides which must be controlled;
5. The formation of nitrogen oxides can be minimized if the combustion chamber is maintained above 1100°C ;
6. Destruction depends on the interaction of a combustion chamber's temperature, dwell time, and turbulence; and,
7. Off-gases and ash must be monitored for chemical constituents, each residual must be treated as appropriate so the entire combustion system operates within the requirements of the local, state, and federal environmental regulators, and hazardous components of the off-gases, off-gas treatment processes, and the ash must reach ultimate disposal in a permitted facility [3].

DESTRUCTION AND REMOVAL EFFICIENCY

In the United States, the Emergency Planning and Community Right-To-Know Act (EPCRA) requires that certain emergency planning activities to be conducted for extremely hazardous

substances (EHSs) in quantities at or above the threshold planning quantity (TPQ). The same chemicals may also have to meet requirements under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) the Clean Air Act. In fact, the EPA updates the so-called list of lists for these substances [5].

Any incineration of wastes containing hazardous substances in the United States requires a permit. The owner or operator of an incinerator is only allowed to burn wastes as specified in the permit and only under operating conditions specified for those wastes. Incinerating new wastes may have to be based on either trial burn results or alternative data to establish appropriate conditions for each of the applicable requirements related to allowable waste feedstocks and operating conditions [6].

An incinerator burning a substance that contains "principal organic hazardous constituents" (POHCs) must be designed, constructed, and maintained so that will achieve a destruction and removal efficiency (DRE) of 99.99% for each POHC designated in its permit for each waste feed. For each such waste feed, the permit will specify acceptable operating limits including the following conditions:

- (1) Carbon monoxide (CO) level in the stack exhaust gas;
- (2) Waste feed rate;
- (3) Combustion temperature;
- (4) An appropriate indicator of combustion gas velocity;
- (5) Allowable variations in incinerator system design or operating procedures; and
- (6) Such other operating requirements as are necessary to ensure compliance with the hazardous waste incineration performance standards (section 264.343 of EPA regulations).
- (7) During start-up and shutdown of an incinerator, hazardous waste (except wastes exempted in accordance with section 264.340 of EPA regulations)

must not be fed into the incinerator unless the incinerator is operating within the conditions of operation (temperature, air feed rate, etc.) specified in the permit.

- (8) Fugitive emissions from the combustion zone must be controlled by:
 - (a) Keeping the combustion zone totally sealed against fugitive emissions; or
 - (b) Maintaining a combustion zone pressure lower than atmospheric pressure; or
 - (c) An alternate means of control demonstrated (with part B of the permit application) to provide fugitive emissions control equivalent to maintenance of combustion zone pressure lower than atmospheric pressure.
- (9) An incinerator must be operated with a functioning system to automatically cut off waste feed to the incinerator when operating conditions deviate from limits established under paragraph (a) of this section.
- (10) An incinerator must cease operation when changes in waste feed, incinerator design, or operating conditions exceed limits designated in its permit.

The destruction and removal efficiency (DRE) is calculated as:

$$\text{DRE} = \frac{W_{\text{in}} - W_{\text{out}}}{W_{\text{in}}} \times 100 \quad (31.3)$$

where W_{in} = rate of mass of waste flowing into the incinerator and W_{out} = rate of mass of waste flowing out of the incinerator.

Extremely hazardous waste constituents require at least 99.9999% DRE.

For example, is an incinerator meeting the federal DRE if, during a stack test, the mass of Chemical X (POHC and EHS) is loaded into incinerator is measured at $W_{\text{in}} = 10 \text{ mg min}^{-1}$ and the mass flow rate of the compound measured downstream in the stack is $W_{\text{out}} = 200 \text{ pg min}^{-1}$ (where p refers to pico, 10^{-12})?

$$\text{DRE} = \frac{10 \text{ mg min}^{-1} - 200 \times 10^{-9} \text{ mg min}^{-1}}{10 \text{ mg min}^{-1}} \times 100$$

$$= 999999.98\% \text{ removal}$$

Even though Chemical X is considered to be “extremely hazardous,” this DRE is better than the “rule of six nines” so the incinerator is operating up to code.

If during the same stack test the mass of Chemical Y loaded into incinerator was measured at the rate of 100 L min^{-1} and the mass flow rate of the compound measured downstream was 1 mL min^{-1} , is the incinerator up to code for this POHC? This is a lower removal rate since 100L are in and 0.001 are leaving, so the $\text{DRE} = 99.999$. This is acceptable, that is, better removal efficiency than 99.99% by an order of magnitude, so long as Chemical Y is not considered an extremely hazardous compound. If it were, then the incinerator would not have met the rule of six nines (it only has five).

From a more qualitative perspective, if either of these compounds are chlorinated, special precautions must be taken when dealing with such halogenated compounds, since even more toxic compounds than those being treated can end up being generated. Incomplete reactions are very important sources of environmental contaminants. For example, these reactions generate products of incomplete combustion (PICs), such as dioxins, furans, carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), and hexachlorobenzene.

3.1.3 Other Thermal Technologies

High-temperature incineration may not be needed to treat many wastes, including most volatile organic compounds (VOCs). Also, in soils with heavy metals, the high temperatures will lead to an increase in the vapor pressure of metals, so they will find their way into the combustion flue gas. High concentrations of volatile trace metal compounds in the flue gas poses complicate pollution control strategies.

When successful in decontaminating soils to the necessary treatment levels, thermally desorbing contaminants from substrates have the benefits over incineration, including lower fuel consumption, no formation of slag, less volatilization of metal compounds, and less complicated air pollution control demands. Beyond monetary costs and ease of operation, a less energy (heat) intensive system can be more advantageous in terms of actual pollutant removal efficiency.

PYROLYSIS

Chemical decomposition induced in organic materials by heat in the absence of oxygen is known as pyrolysis, that is, it is the thermal conversion of organic matter in the total absence of oxygen at relatively low temperatures of between 500°C and 800°C and short vapor residence times of 3–1500s. It is practically impossible to achieve a completely oxygen-free atmosphere; so pyrolytic systems run with less than stoichiometric quantities of oxygen. Because some oxygen will be present in any pyrolytic system, there will always be a small amount of oxidation. Also, desorption will occur when volatile (i.e., vapor pressure $> 10^{-2} \text{ kPa}$) or semivolatile (i.e., vapor pressure between 10^{-2} and 10^{-5} kPa) compounds are present in the feed.

During pyrolysis [11], organic compounds are converted to gaseous components, along with some liquids, as coke, that is, the solid residue of fixed carbon and ash. CO, H_2 , and CH_4 and other hydrocarbons are produced. If these gases cool and condense, liquids will form and leave oily tar residues and water with high concentrations of total organic carbon (TOC). The secondary gases need their own treatment, such as by a secondary combustion chamber, by flaring, and partial condensation. Particulates must be removed by additional air pollution controls, for example, fabric filters or wet scrubbers.

Many of the same conventional thermal treatment methods used for incineration, such as

rotary kiln, rotary hearth furnace, or fluidized bed furnace, are also used for waste pyrolysis. Kilns or furnaces used for pyrolysis may be of the same design as those used for combustion discussed earlier, but operate at lower temperatures and with less air than in combustion.

Pyrolysis allows for separating organic contaminants from various wastes and may be used to treat a variety of organic contaminants that chemically decompose when heated (i.e., "cracking"). Pyrolysis is not effective in either destroying or physically separating inorganic compounds that coexist with the organics in the contaminated medium.

3.1.4 Specialized Thermal Systems

Other promising thermal processes include high-pressure oxidation and vitrification. High-pressure oxidation combines two related technologies, that is, wet air oxidation and supercritical water oxidation, which combine high temperature and pressure to destroy organics. Wet air oxidation can operate at pressures of about 10% of those used during supercritical water oxidation, an emerging technology that has shown some promise in the treatment of polychlorinated biphenyls (PCBs) and other stable compounds that resist chemical reaction. Wet air oxidation has generally been limited to conditioning of municipal wastewater sludges, but can degrade hydrocarbons (including PAHs), certain pesticides, phenolic compounds, cyanides, and other organic compounds. Oxidation may benefit from catalysts.

Vitrification uses electricity to heat and destroy organic compounds and immobilize inert contaminants. A vitrification unit has a reaction chamber divided into two sections: the upper section to introduce the feed material containing gases and pyrolysis products, and the lower section consisting of a two-layer molten zone for the metal and siliceous components of the waste. Electrodes are inserted into the waste solids, and graphite is applied to the surface to enhance its electrical conductivity.

A large current is applied, resulting in rapid heating of the solids and causing the siliceous components of the material to melt as temperatures reach about 1600°C. The end product is a solid, glass-like material that is very resistant to leaching.

As discussed in [Chapter 20](#), thermal processing of plastics must be managed very carefully to prevent the release of highly toxic compounds. As those who have had to fight fires in municipal landfills know all too well, plastic fires can produce very noxious and toxic compounds. In fact, burning plastics can release over 450 different organic compounds [12]. The role of oxygen, that is, the relative amount of combustion and pyrolysis, is a major determinant as to the actual amounts and types of compounds released. Temperature is also important, but a direct relationship between temperature and pollutants released has not been established. For example, the low density polyethylene pyrolysis of plastics generates some compounds at lower temperatures, whereas for others the optimal range is at higher temperatures (see Fig. 20.7 in [Chapter 20](#)). However, the aliphatic compounds (e.g., 1-dodecene, 9-nonadecane, and 1-hexacosene) can be generated in higher concentrations at lower temperatures (about 800°C), while the aromatics need higher temperatures (see Fig. 20.8 in [Chapter 20](#)).

3.2 Solidification and Stabilization

Physical treatment systems can be designed to improve handling and the physical characteristic of the waste, decrease the surface area across which transfer or loss of contained pollutants can occur, and limit the solubility of, or detoxify, any hazardous constituents contained in the wastes. In solidification, these results are obtained primarily, but not exclusively, by producing a monolithic block of treated waste with high structural integrity. Stabilization techniques limit the solubility or detoxify waste contaminants even though the physical characteristics of the waste may not be changed.

Stabilization usually involves the addition of materials that ensure that the hazardous constituents are maintained in their least soluble or least toxic form.

3.3 Disposal

After treatment is completed, an inorganic residue remains that must be disposed of safely. Most often, this residue has no economic value. There are five options for disposing of hazardous waste. (1) Underground injection wells are steel- and concrete-encased shafts placed deep below the surface of the earth into which hazardous wastes are deposited by force and under pressure. Some liquid waste streams are commonly disposed of in underground injection wells. (2) Surface impoundment involves natural or engineered depressions or diked areas that can be used to treat, store, or dispose of hazardous waste. Surface impoundments are often referred to as pits, ponds, lagoons, and basins. (3) Landfills are disposal facilities where hazardous waste is placed in or on land. Properly designed and operated landfills are lined to prevent leakage and contain systems to collect potentially contaminated surface water runoff. Most landfills isolate wastes in discrete cells or trenches, thereby preventing potential contact of incompatible wastes. (4) Land treatment is a disposal process in which hazardous waste is applied onto or incorporated into the soil surface. Natural microbes in the soil break down or immobilize the hazardous constituents. Land treatment facilities are also known as land-application or land-farming facilities. (5) Waste piles are noncontainerized accumulations of solid, nonflowing hazardous waste. While some are used for final disposal, many waste piles are used for temporary storage until the waste is transferred to its final disposal site.

Of the hazardous waste disposed of on land, nearly 60% is disposed of in underground

injection wells, approximately 35% in surface impoundments, 5% in landfills, and <1% in waste piles or by land application.

3.4 Comprehensive Treatment Facilities

In the United States, Canada, and many western European countries, there are large facilities capable of treating and disposing of many types of hazardous wastes. These facilities are able to realize economies of scale by incorporating many treatment processes that might not be economical for individual generators. Comprehensive facilities are also able to exploit the synergistic opportunities made possible by having many different types of waste present at a single site. These include using waste acids and alkalis to neutralize one another, waste oxidants to treat cyanides, and organic contaminants in water, salts and acids to salt out organic compounds from wastewater, on-site incinerators to dispose of organic vapors generated by other on-site processes, ash and calcium and magnesium oxides to aid in stabilization processes, and combustible solids and liquids to produce blended liquid fuels.

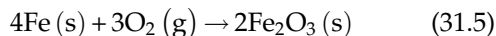
3.5 Chemical Treatment

The chemical structure of the constituents of the waste can be altered to produce either an innocuous or a less hazardous material by taking advantage of chemical reactions. This can be said of many biological processes as well, but so-called chemical treatment processes are understood to be abiotic (i.e., chemical reactions anywhere outside of a living organism). Thus it is possible to use abiotic and biotic reactions to treat organic and inorganic wastes. Any of the four categories of chemical reactions are available to treat hazardous wastes: synthesis or combination, decomposition, single replacement, and double replacement.

Synthesis or combination. In combination reactions, two or more substances react to form a single substance:



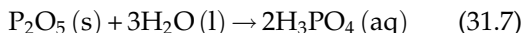
Two types of combination reactions are important in environmental systems: formation and hydration. Formation reactions are those where elements combine to form a compound. An example is the formation reaction of ferric oxide:



Hydration reactions involve the addition of water to synthesize a new compound, for example, in reaction when calcium oxide is hydrated to form calcium hydroxide:



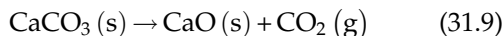
Hydration reactions also occur when phosphate is hydrated to form phosphoric acid:



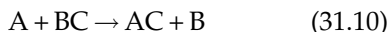
Decomposition. Often referred to as degradation when discussing organic compounds in toxicology, environmental sciences, and engineering, in decomposition reactions:



one substance breaks down in two or more new substances. For example, in reaction calcium carbonate breaks down into calcium oxide and carbon dioxide:

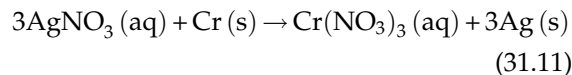


Single replacement (single displacement). This reaction commonly occurs when one reactant replaces another reactant:

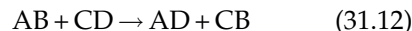


For example, a less toxic ion can be used to replace a more toxic ion, or if the cationic replacement makes collection, disposal, or

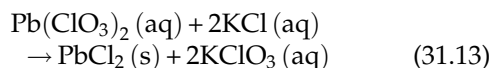
additional treatment easier. A simple replacement occurs when trivalent chromium replaces monovalent silver:



Double replacement (metathesis or double displacement). In metathesis reactions, molecules exchange their cations and anions:



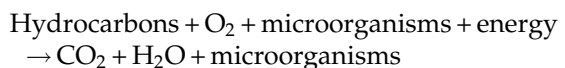
These reactions commonly are used to precipitate metals out of solution, such as when lead is precipitated, as in reaction of a lead salt with an acid such as potassium chloride:



Abiotic chemical processes are attractive because they usually produce minimal air emissions, they can often be carried out on the site of the waste generator, and some processes can be designed and constructed as mobile units. A few commonly applied chemical treatment processes are neutralization, precipitation (e.g., waste streams containing heavy metals), ion exchange, dehalogenation (especially dechlorination and debromination), and oxidation-reduction for detoxifying toxic wastes.

3.6 Biodegradation of Hazardous Waste

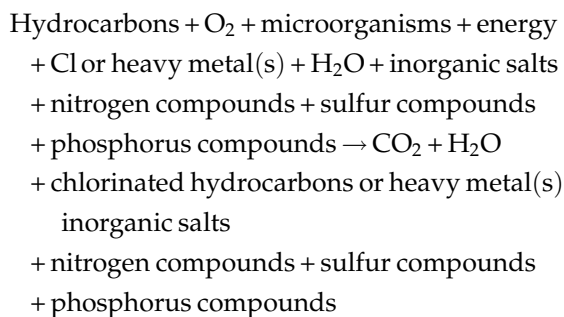
All four types of chemical reactions discussed before can take place within an organism. Environmental biotechnology is the use of microorganisms to decompose organic wastes into water, carbon dioxide, and simple inorganic substances, or into simpler organic substances such as aldehydes and acids [13]. Contaminants, if completely organic in structure are, in theory, fully destructible using microorganisms with the engineering inputs and outputs summarized as:



(31.14)

To treat hazardous wastes using biotechnology, the waste is mixed with oxygen and aerobic microorganisms, sometimes in the presence of an external energy source in the form of added nutrition for the microorganisms. The biodegradation occurs in the biofilm around the microbes, as well as within the microbes. In time, the by-products of gaseous carbon dioxide and water are produced which exit the top of the reaction vessel, while a solid mass of microorganisms is produced to exit the bottom of the reaction vessel.

If the waste contains other chemical constituents, chlorine, and/or heavy metals, and if the microorganisms can withstand and flourish in such an environment, the simple input and output relationship in [reaction \(31.14\)](#) is modified to become:



(31.15)

If the microorganisms survive in this complex and potential hostile environment, waste products may be generated with greater toxicity than the original wastes, for example, containing newly formed chlorinated hydrocarbons, higher heavy metal concentrations, as well as more mobile or more toxic chemical species of heavy metals.

All bioreactor systems rely on a population of microorganisms to metabolize organic contaminants, ideally into the harmless by-products of

$\text{CO}_2 + \text{H}_2\text{O}$. Reactors also generate heat and other energy by-products. The microorganisms must be either initially cultured in the laboratory to be able to metabolize a specific organic waste or must be given sufficient time to evolve to be able to digest the contaminant. The waste manager must plan for and undertake extensive and continual monitoring and fine-tuning of each microbiological processing system during its operation.

Bioremediation success depends on the growth and survival of microbial populations and the ability of these organisms to come into contact with the substances that need to be degraded into less toxic compounds. Sufficient numbers of microorganisms must be present and active to make bioremediation successful and the preferred cleanup choice. Also, the microbial environment must be habitable for the microbes to thrive. Concentrations of compounds can be so high that the environment is toxic to microbial populations. Therefore the design must either offer a method other than bioremediation or modify the environment (e.g., dilution, change in pH, pumped oxygen, adding organic matter, etc.) to make it habitable. An important modification is the removal of nonaqueous phase liquids (NAPLs) since the microbes' biofilm and other mechanisms usually work best when the microbe is attached to a particle. Thus most of the NAPLs need to be removed, including by vapor extraction.

Physical, chemical, and biological factors drive the selection of bioremediation strategy. For example, low permeability soils, like clays, are difficult to treat, since liquids (water, solutes, and nutrients) are difficult to pump through these systems. Usually bioremediation works best in soils that are relatively sandy, allowing mobility and greater likelihood of contact between the microbe and the contaminant. Thus an understanding of the environmental conditions sets the stage for problem formulation based on the factors at work and the resulting threats to health and environmental quality.

Bioremediation is a process of optimization, that is, selecting options among a number of biological, chemical, and physical factors. These include correctly matching the degrading microbes to conditions, understanding and controlling the movement of the contaminant (microbial food) so as to come into contact with the microbes, and characterizing the abiotic conditions controlling both of these factors. Optimization can vary among options, such as artificially adding microbial populations known to break down the compounds of concern. Compound degradation can be quite specific to microbial genera. Only a few species can break down certain organic compounds. The number of microbe genera that can degrade a molecule decreases with the complexity of the molecule, including the presence of certain functional groups, for example, Cl and Br substitution.

Two major limiting factors of any biodegradation process are toxicity to the microbial population and inherent biodegradability of the compound. As the biology of microbial biodegradation has become better understood (e.g., mechanisms and modes of action), efficacy has improved. For example, the methanogenic granular sludge structure has been found to play a key role in high-rate anaerobic processes [14]. Granular sludge is an excellent example of a system, since it is an aggregation of several metabolic groups of bacteria living in synergism. The factors that make granular sludge environments hospitable for these bacteria may be replicated in other environments, both in situ and ex situ.

The benefits of biological treatment systems include (1) the potential for energy recovery; (2) volume reduction of the hazardous waste; (3) detoxification as selected molecules are reformulated; (4) the basic scientific principles, engineering designs, and technologies are well understood from a wide range of other applications including municipal wastewater treatment at facilities; (5) application to most organic

contaminants which as a group compose a large percentage of the total hazardous waste generated nationwide; and (6) the possibility to scale the technologies to handle a single liter or kilogram or millions of liters or tonnes of waste per day.

The drawbacks of the biotreatment systems include (1) the operation of the equipment requires very skilled operators and is costlier as input contaminant characteristics change over time and correctional controls become necessary; and (2) ultimate disposal of the waste microorganisms is necessary and particularly troublesome and costly if heavy metals and/or chlorinated compounds are found during the monitoring activities. In general, hazardous waste containing heavy metals should not be bioprocessed. Variations on three different types of bioprocessors are available to treat hazardous wastes: trickling filter, activated sludge, and aeration lagoons.

3.6.1 Mixed Hazardous Waste Reactors

In nature, the degradation varies in space and time according to available oxygen, moisture, nutrients, and biota. Thus natural systems are usually a mixture of aerobic and anaerobic systems. Engineers have applied this to mixed reactor systems, most notably the trickling filter, which a bed of rocks (~10 cm diameter, but highly variable in size and shape) enclosed in a rectangular or cylindrical structure, through which wastes are carried (see Fig. 31.8). Biofilms are selected from laboratory studies and encouraged to grow on the rocks. As the liquid waste moves with gravity downward through the bed, the microorganisms contact the organic contaminant/food source and ideally metabolize the waste into $\text{CO}_2 + \text{H}_2\text{O}$ + microorganisms + energy. Oxygen is supplied by blowers from the bottom of the reactor and passed upward through the bed. The treated waste moves downward through the bed subsequently enters a quiescent tank where the microorganisms that are sloughed off the rocks

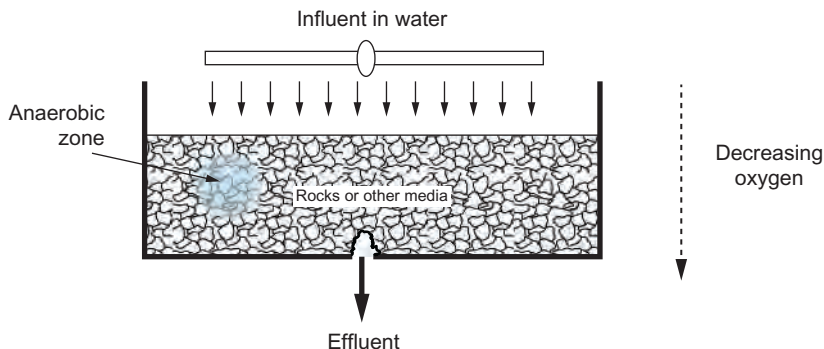


FIG. 31.8 Trickling filter treatment system, which includes zones of varying concentrations of dissolved oxygen, that is, it is a mixed reactor for treating hazardous wastes. Adapted from D.A. Vallero, J.J. Peirce, *Engineering the Risks of Hazardous Wastes*, Butterworth-Heinemann, Burlington, MA, 2003, pp. xxi, 306 p.

are settled, collected, and disposed. Trickling filters are considered mixed treatment systems because aerobic bacteria grow in the upper, higher oxygen layers of the media, while anaerobes grow in the regions lower in the system.

Another mixed reactor system used to treat hazardous waste is the landfill. The hazardous waste landfill is structured like the municipal landfill described in [Chapter 12](#) and applies the same physical, chemical, and biological processes. However, special considerations must be made for hazardous wastes, for example, more efficient barriers to limit flows away from the landfill. Hazardous waste landfills must also be aware of potential toxicity to the microbial populations, for example, may require pretreatment before certain wastes are allowed.

Hazardous waste landfills often have highly persistent and recalcitrant chemical compounds that resist biodegradation, requiring bioaugmentation and biostimulation. Bioaugmentation is a method of helping indigenous microbial populations break down waste by adding new microbes that have been shown to degrade the compounds of concern, especially oil-degrading bacteria [15]. Biostimulation is the process of adding nutrient, oxygenating and injecting water into the cells of the landfill bioreactor. These approaches can also include genetic enhancements of the microbes.

As is often the case in environmental engineering, theory forms the basis for the application, but real-world conditions dictate the approach. Thus a hazardous waste management plan may center around a landfill, but may also be combined with other technologies. Notably, advanced physicochemical treatment technologies can be blended with the landfill reactor's biological processes. For example, adding enriched nitrifying membrane bioreactor sludge can enhance the destruction of phenolic compounds [16]. Fenton oxidation, that is, using hydrogen peroxide (H_2O_2) as an oxidation agent and divalent iron (Fe^{2+}) as a catalyst, can improve degradation rates of hazardous waste landfill leachate [17].

In North America, landfill regulations call for a system that minimizes liquid infiltration into the solid waste mass by controlling the amount of moisture allowed into these landfills. A hazardous waste landfill is defined as a disposal facility or part of a facility where hazardous waste is placed in or on land and which is not a pile, a land treatment facility, a surface impoundment, an underground injection well, a salt dome formation, a salt bed formation, an underground mine, a cave, or a corrective action management unit [18]. A hazardous waste landfill is a type of treatment, storage, and disposal facility (TSDF) and as such must

be appropriately permitted and the permit will specify all design and operating practices necessary to ensure compliance. All hazardous waste landfills must include a run-on control system, a run-off management system, and control of the wind dispersal of particulate matter. The run-on control system's capacity must prevent flow onto the active portion of the landfill during peak discharge of a 25-year storm event. The run-off management system must be able to collect and control water from a 24-h or a 25-year storm and the run-off's chemical constituents must be tested. The landfill design must be based on this information. In addition to the design, the landfill must be operated to prevent migration of contaminants off-site. For example, holding tanks and basins designed to retain run-on and run-off control systems must be emptied expeditiously after storm events.

The design and operation of landfills must also be properly documented. Each hazardous waste landfill needs a map with the exact topological and dimensional information, for example, depth of each cell with respect to permanently surveyed benchmarks. The contents of each cell and the approximate location of each hazardous waste type within the cell must be recorded.

The contents of a hazardous waste landfill are strictly enforced. For example, bulk or noncontainerized liquid waste or waste containing free liquids are not permitted. The exemption is containers holding free liquids if they meet one of the following standards:

- all free-standing liquid has been removed by decanting, or other methods, mixed with sorbent or solidified so that free-standing liquid is no longer observed, or otherwise eliminated,
- the container is very small, such as an ampule (i.e., hermetically sealed vial),
- the container is designed to hold free liquids for use other than storage (e.g., a battery or capacitor),

- the container is a lab pack.

In order to dispose of the sorbents used to treat free liquids in a hazardous waste landfill, the sorbent must be nonbiodegradable. Approved sorbents include:

- inorganic minerals, other inorganic materials, and elemental carbon,
- high molecular weight synthetic polymers, except for polymers derived from biological material or polymers specifically designed to be degradable,
- mixtures of nonbiodegradable materials.

Unless they are very small, containers must be at least 90% full and crushed, shredded, or similarly reduced in volume to the maximum practical extent.

As discussed in [Chapter 12](#), dry-tomb landfill designs produce less leachate, but severely limit biodegradation, since moisture is a limiting factor for biofilm production and microbial metabolism. In any moisture condition, long-term monitoring is required at and near hazardous waste treatment and storage facilities. Current regulations require leachate and gas emissions to be monitored during and postclose for many years, until any risk from the waste has been abated.

The rate of microbial degradation in landfills can be enhanced, especially by increasing the moisture content of the waste. This can be by increasing the amount of water in the strata and by leachate recirculation [19] (see Fig. 12.1 in [Chapter 12](#)).

Landfill reactions are predominantly aerobic in the early stages and become increasingly anaerobic with time. The majority of landfill decomposition by volume occurs under anaerobic conditions. However, the long-term conditions, that is, final maturation stage, nears a dichotomy between anaerobic and aerobic regions. Thus nearly the same amount of CO_2 and CH_4 is emitted from the landfill during this near-steady-state stage (see Fig. 12.7 in [Chapter 12](#)).

Upon entry to a hazardous waste landfill, as indicated by rates of chemical oxygen demand (COD_s), the organic material in solid phase decays rapidly as larger organic molecules degrade into smaller molecules. These smaller organic molecules in the solid phase undergo dissolution and move to the liquid phase (COD_L), with subsequent hydrolysis of these organic molecules. The smaller molecules are transformed and volatilize as CO_2 and CH_4 , with remaining biomass in solid and liquid phases. Thus the first two phases release little material volume to the leachate. However, the biodegradable organic matter of the waste undergoes rapid volume loss. Meanwhile, the COD of the leachate (COD_L) rises with the increasing ratio of recalcitrant compounds to reactive compounds in the leachate [20].

The syntrophy and other mechanisms at work in the municipal landfill also occur in the hazard waste biolandfill (see Fig. 12.1 in Chapter 12). Thus it is crucial to maintain the proper microbial population to ensure efficient and effective biodegradation.

3.6.2 Aerobic Hazardous Waste Reactors

The presence and quantity of oxygen are always key factors in designing hazardous waste treatment systems. Numerous hazardous wastes are best degraded under aerobic, that is, excess oxygen conditions. In an activated sludge system, microorganisms are recycled within the system (see Fig. 31.9). This reuse enables the microorganisms to evolve over time and adapt to the changing characteristics of the hazardous waste.

In an activated sludge system, a tank of liquid hazardous waste is injected with a mass of microorganisms. Oxygen is supplied through pipes in the aeration basin as the microorganisms come in contact, become adsorbed, and metabolize the waste. For complete and ideal conditions, this would convert all organic matter into $CO_2 + H_2O + \text{microorganisms} + \text{energy}$. The

heavy, that is, well-fed, microorganisms then flow into a quiescent tank where they settle by gravity and are collected and disposed. Depending on the operating conditions of the facility, some or many of the settled (now hungry) and active microorganisms are returned to the aeration basin where they feed again. Liquid effluent from the activated sludge system may require additional microbiological and/or chemical processing prior to release into a receiving stream or sewer system.

Aeration lagoons or ponds treat liquid and dissolved contaminants for long terms, from months to years (Fig. 31.10). Persistent organic molecules, those not readily degraded in trickling filter or activated sludge systems, are potentially broken down by certain microbes into $CO_2 + H_2O + \text{microorganisms} + \text{energy}$, if given enough time. The ponds are open to the weather and ideally oxygen is supplied directly to the microorganisms from the atmosphere. Their dimensions vary but some general configurations based on laboratory experiments and pilot studies include:

- Design: Pond size: 1–8 ha (0.45–20 acres);
- Design: Pond depth: 0.3–9 m (1–30 ft);
- Design: Detention time: days to months to possibly years;
- Operation: In series with other treatment systems, other ponds, or stand-alone;
- Operation: The flow to the pond is either continuous or intermittent; and
- Operation: The supply of additional oxygen to the system through blowers and diffusers may be required, that is, active systems.

The slurry-phase lagoon activation is a similar aerobic system in which air and contaminated soil or other material contact one another to promote biodegradation. Such a system can treat an entire batch of sludge in a single operation. These are usually <0.8 ha (2 acres), with geometry and depth dependent upon the type of liner material, as well as the waste and slurry characteristics and thickness. Larger

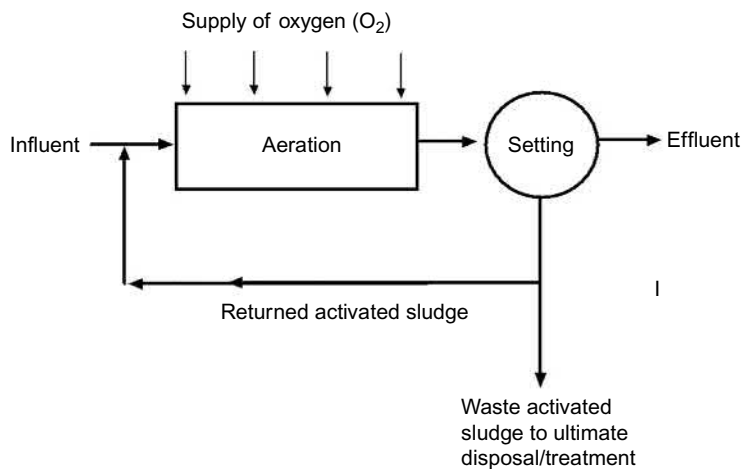


FIG. 31.9 Aerobic treatment approach to degrade hazardous waste. In this activated sludge treatment system, the waste is combined with recycled biomass and aerated to maintain a target dissolved oxygen (DO) content. Organisms use the organic components, expressed as biochemical oxygen demand (BOD) of waste as food, decreasing the organic levels in the wastewater. Oxygen concentrations must be controlled to maintain optimal treatment efficiencies. One means of achieving optimal DO content is tapered aeration, which provides highest concentrations of oxygen near the influent to accommodate the large oxygen demand from microbes as waste is introduced to the aeration tank (photo). *Adapted from D.A. Vallero, J.J. Peirce, Engineering the Risks of Hazardous Wastes, Butterworth-Heinemann, Burlington, MA, 2003, pp. xxi, 306 p.; photo courtesy of D.J. Vallero.*

systems require sectioning off into smaller lagoon compartments (Fig. 31.10B). Total solids content ranges from 5% to 20% [9].

Slurry systems are also used ex situ in tanks where higher degradation rates and greater engineering controls are needed (e.g., to treat soils and other media contaminated with very toxic and/or particularly recalcitrant organic contaminants). These stirred tank bioreactors

can receive sequenced batches or continuously fed sludge.

Another pond-like biological treatment system (Fig. 31.10C) is the engineered and constructed wetland, which operates as a biofilter. Wetlands naturally contain diverse and abundant microbial populations. These features are combined with growth, nutrient extraction, photosynthesis, and ion exchange processes of

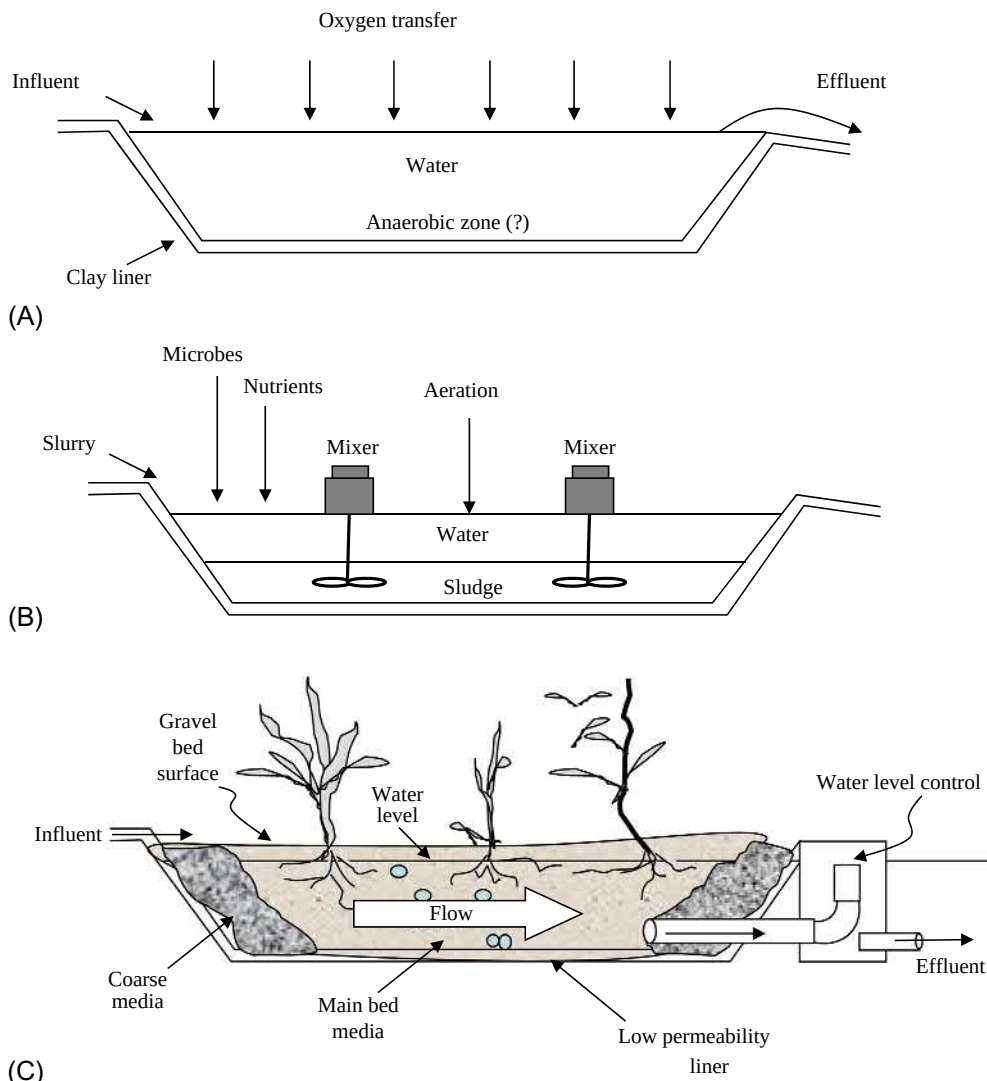


FIG. 31.10 (A) Passive system: aeration pond. (B) Active system: in situ slurry-phase lagoon. (C) Combined active and passive system: engineered and constructed wetland. All three systems make use of microbes, nutrients, and oxygen, but the active system increases the contact between the microbes and organic matter by mechanically mixing the sludge layer (which contains the organic contaminants to be degraded) with the water in the lagoon. The engineered wetland also incorporates plant processes in the degradation process. Adapted from EPA/540/A5-91/009, *Pilot-Scale Demonstration of Slurry-Phase Biological Reactor for Creosote-Contaminated Soil: Applications Analysis Report*, 1993; S. Wallace, *Engineered wetlands lead the way*, *Land Water* 48(5) (2009).



FIG. 31.11 Engineered and constructed wetland system in San Diego, California, utilizing macrophytes, that is, water hyacinths (*Eichhornia* spp.). The system takes advantage of both microbial and larger plant species (bioremediation and phytoremediation, respectively). Source: C.P. Gerba, I.L. Pepper, *Wastewater treatment and biosolids reuse*, in: *Environmental Microbiology*, second ed., Elsevier Inc., USA, 2009, pp. 503–530.

plants (Fig. 31.11). For example, gasoline-contaminated groundwater has been bioremediated using a radial flow constructed wetland system in Casper, Wyoming. In this system, subsurface beds of crushed concrete reclaimed from a closed refinery were insulated with 15 cm layers of mulch. Above these layers bulrushes, switchgrass, and cordgrass were planted in separate sections of the wetland system. About 2650 m^3 (700,000 US gallons) of water are passively treated each day, with large reductions in benzene and other hydrocarbons. The rock/mulch insulated layers allow biological activity to continue throughout the year, even in the cold Wyoming winters. Since this is a passive treatment system, it is cost effective compared to most active systems. As evidence, its estimated construction costs were about 20% of a pump-and-treat system that meet similar

criteria, for example, air stripping and catalytic oxidation [21].

The crucial engineering concerns in the design and operation of ponds and other environmental biotechnologies are the identification and maintenance of microbial populations that metabolize the specific contaminant of concern. Once selected, the conditions most favorable to the microbial populations can be determined and controlled.

The fluid dynamics and biological principles of the slurry-phase lagoon (Fig. 31.10B) and the engineered wetland (Figs. 31.10C and 31.11) can be used to treat air pollutants in a simple biofilter (Fig. 31.12). However, polluted air rather than water is pumped into the system and mixed with water and pushed into the bottom of a 1-m deep trench covered with unconsolidated material (soil or compost).

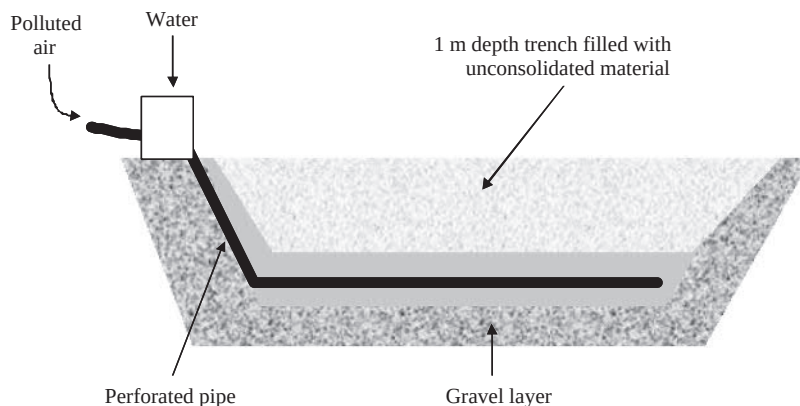


FIG. 31.12 Biofilter system used to treat air contaminated with organic pollutants. Adapted from A.H. Scragg, *Environmental Biotechnology*, Oxford University Press, New York, 2005.

The saturated air and water containing the organic contaminants move into the gravel and contact the microbial biofilm. The vapor pressure allows the more volatile compounds to move first through the media, but with time less volatile compound vapors will percolate through the unconsolidated material. During percolation, the air contacts the biofilm of microbes sorbed to the particles, which degrade the organic contaminants. A more intricate version is the packed bed biological control system to treat volatile compounds anaerobically.

Highly hazardous wastes often will not be allowed to be treated in these open systems, without very strong containment systems surrounding them in all directions, that is, including the need for covers and collectors for any volatilized or aerosolized material emitted to the air. In addition to scientific and engineering constraints, legal restrictions and public perception may prevent in situ treatment.

3.6.3 Anaerobic Hazardous Waste Reactors

Anaerobic and aerobic processes frequently occur in different parts of the same system, as mentioned in the trickling filter discussions. One of the challenges of an aerobic system is maintaining the aerobes' contact with molecular oxygen. If the reactor's oxygen level drops or if

the tank is not completely mixed, pockets of anoxic and reduced conditions can lead to localized anaerobic conditions within the bioreactor. This is unacceptable if the bioreactions depend solely on oxygen as the electron acceptor. In fact, the foul smells from wastewater treatment facilities can usually be attributed to some part of the plant or the receiving water "going anaerobic," meaning that sulfur compounds are being reduced to odiferous forms, for example, hydrogen sulfide and mercaptans. The benefit of anaerobic conditions is that they can be used to degrade otherwise recalcitrant organic compounds (see Fig. 31.13).

Anaerobic degradation consists of a series of steps whereby polysaccharides, proteins, fats, and other complex polymeric materials are hydrolyzed by the microbes. These microbial reactions, catalyzed by enzymes, generate products with greater aqueous solubility. The new compounds are secreted by the microorganisms into the biofilm where they can be transported, predominantly by advection, diffusion, and receptor binding, across cellular membranes. Advective transport includes the transport with the flow of the mass, that is, in this instance the water flowing into and through the cell membrane. Diffusion is the molecular transport, that is, a chemical compound in the waste reaches



FIG. 31.13 Anaerobic treatment system. The lighter substances have migrated to the surface. These may be fats that have been separated physically during the treatment process, or bubbles from gases, such as methane, that are produced when the anaerobes degrade the wastes. Note that although this is an anoxic chamber, a thin film layer at the surface will be aerobic because it is in contact with the atmosphere. *Photo courtesy of D.J. Vallero.*

the biofilm from which its molecular concentration is higher than that of the cell membrane and enters the cell. The actual degradation of the chemical, however, is by receptor binding. In this case, the chemical (known as the ligand) is usually aided by a transport protein (enzyme—biological catalyst) that is specific to a class of chemicals. The enzyme-ligand complex binds with a receptor on the cell membrane and is transported into the cell. This process can be likened to a key (ligand) that fits into a lock (receptor) that allows the chemical to enter the cell.

Ultimately, if the anaerobic biodegradation is successful, the production and ensuing escape of methane indicates that the organic material has been stabilized and degraded. The design

of anaerobic systems needs to ensure that the retention time of the solids is sufficient for contact and reaction by the microbes with the substrate [22]. For example, if the input of relatively easily degradable organics is too rapid, this can lead to acidic and toxic conditions, with the buildup of organic acids, which can foul the reactor by inhibiting methanogenesis (i.e., instead of reaching the desired methane-water products, the system is stuck in the acid production steps.)

Acclimatization of the microorganisms to a substrate can take several weeks. The biodynamics of the bioreactor affect anaerobic digestion rates, including temperature, pH, and concentration of toxic substances. The conventional anaerobic treatment process consists

of a reactor containing waste and biosolids (sludge containing large microbial populations). As in the aerobic, activated sludge systems, these biosolids can be added continuously or in semibatches, whereupon they are mixed in the bioreactor. In theory, the anaerobic digester is a once-through, completely mixed, reactor. If so, the hydraulic retention time (HRT) equals the solids retention time (SRT). This means that efficiency depends directly on the contact with the biosolids, that is, the SRT. However, HRT and SRT can be decoupled for increased bioremediation efficiency. For example, an anaerobic upflow filter (AF) can substantially improve anaerobic degradation volumes and rates, since the filter can catch and sustain high concentrations of biosolids. By holding the solids, attenuated SRTs allow for much larger throughput which is needed to degrade low-strength organic wastes under feasible, environmental conditions (e.g., ambient temperatures and barometric pressures).

A bed upflow reactor is another anaerobic system, but depends on the sorption of biomass on the surfaces of media. This is done by passing liquid solutions of the organic compounds to be treated upward through a bed of sand-sized particles at a velocity necessary to fluidize and partially expand the sand bed. More recently, the upflow anaerobic sludge blanket process (UASB) takes advantage of the inherent properties of flocculation and settling of anaerobic sludge, allowing for much higher HRT loadings and partitioning of gases (e.g., H_2 , CH_4) from the sludge solids. The UASB is based on two biochemodynamic processes (see Fig. 31.14): separation of solids and gases from the liquid and degradation of biodegradable organic matter. If heavy mechanical agitation is avoided, unlike the other aerobic digesters, a separate settler with biosolids return pump is not needed, so reactor volume can flow consistently through the systems. Unlike the fluidized bed reactor, high rate effluent recirculation and pumping are also eliminated. The biogas

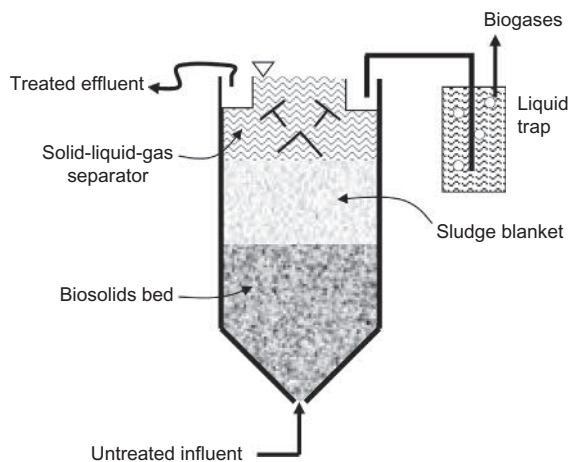


FIG. 31.14 Schematic of upflow anaerobic sludge blanket system. Adapted from D. Christensen, J. Gerick, J. Eblen, *Design and operation of an upflow anaerobic sludge blanket reactor*, *J. Water Pollut. Control Fed.* (1984) 1059–1062.

production enhances continuous contact between substrate and anaerobes. The UASB reactor, under optimal conditions, can be assumed to be a completely mixed reactor. The contact of the biosolids with the incoming organic liquids is enhanced by the agitation caused by the release of gases from the biodegradation, along with an inlet that evenly distributes incoming materials in the lower level of the reactor.

Biological treatment systems do not alter or destroy inorganic substances, and high concentrations of such materials can severely inhibit decomposition activity. Thus chemical or physical treatment may be required to extract inorganic materials from a waste stream prior to biological treatment.

4 ABANDONED DISPOSAL SITES

Many countries have sites where hazardous waste has been disposed of improperly in the past and where cleanup operations are needed to restore the sites to their original state. In the

United States, about 20,000 of these sites have been identified and approximately 2000 sites require immediate action. In the United States, these sites are treated differently from those regulated under RCRA. This is because there is often no clear means of removing wastes or remediating problems (e.g., the ownership is unknown, the former owner is bankrupt, or there are numerous potentially responsible parties). The Comprehensive Environmental Response, Compensation and Liability Act of 1980 (better known as Superfund) was enacted in response to the discovery of toxic waste dumps in the 1970s [23]. The law allows the EPA to clean up abandoned sites and to compel responsible parties to perform cleanups or reimburse the government for cleanups [24].

Canada has an estimated 1000 abandoned hazardous waste sites, including coal tar pits, leaky landfills, old plant sites, and storage facilities. When a polluter cannot be charged with the task of remediation, Canada's federal government enters into agreements with individual provincial and territorial governments to clean up these high-risk properties. This happens when a responsible party cannot be found, or where the owner is unable or unwilling to

finance a remediation project [25]. Many European sites have also been addressed. Denmark, the Netherlands, and Sweden have listed sites requiring immediate attention.

Environmental regulations lay out explicit steps for cleaning up contamination. In the United States, the potential or confirmed releases of hazardous substances are evaluated and prioritized during the Superfund site assessment process. The federal government, states, or tribal agency use the Hazard Ranking System (HRS) criteria to guide the process. The HRS is a numerical screen based on information from preliminary, limited investigations. It helps to assess the relative potential of sites to pose a threat to human health or the environment. After a site is identified, a series of assessments evaluate the potential need for and extent of remedial cleanup [26]. Fig. 31.15 shows the major steps and components of the site assessment process. The assessment uses data to identify, evaluate, and rank hazardous waste sites based on HRS criteria. It is the principal basis for placing uncontrolled waste sites on the National Priorities List (NPL). Sites with HRS scores of 28.5 or greater are eligible for placement on the NPL. Only sites on the NPL are eligible for Superfund Trust Fund-financed

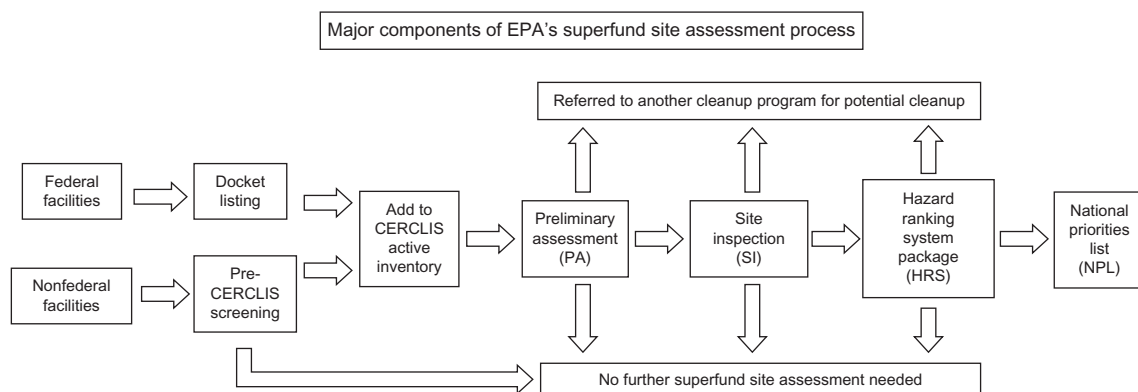


FIG. 31.15 Steps in a contaminated site cleanup, as mandated by the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (Superfund). Source: U.S. Environmental Protection Agency, *Superfund Site Assessment Process*, 2018. Available from: <https://www.epa.gov/superfund/superfund-site-assessment-process>.

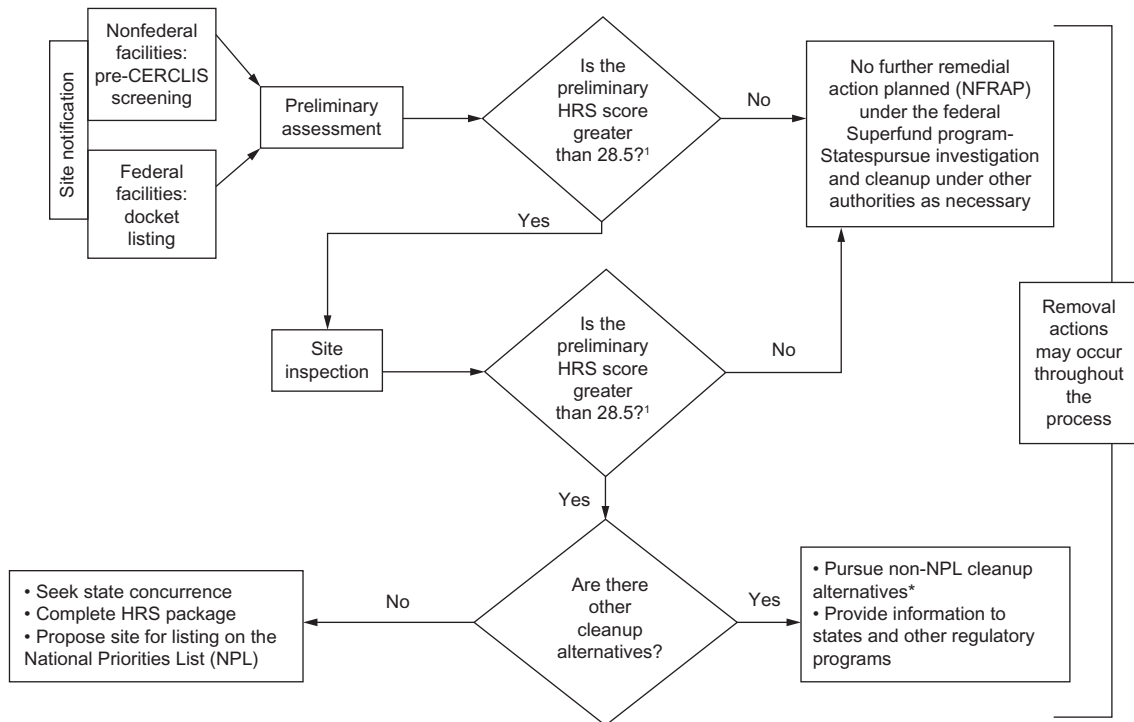


FIG. 31.16 Decision flowchart for selecting candidate abandoned hazardous waste sites for cleanup in the United States. Source: U.S. Environmental Protection Agency, *Superfund Site Assessment Process*, 2018. Available from: <https://www.epa.gov/superfund/superfund-site-assessment-process>.

remedial actions. Fig. 31.16 shows the sequence of steps in the site assessment process.

The site assessment process [27] begins when a site is discovered or when citizens, states, tribes, or other environmental programs notify the EPA of a site. For federal facilities, that is, operations of U.S. governmental agencies, the process starts when a facility is listed on the Federal Agency Hazardous Waste Compliance Docket. Nonfederal sites undergo prescreening to determine whether the Superfund site assessment process is appropriate. A federal facility is automatically placed on the docket. A site discovery date as logged for a site that has been identified as appropriate for the site assessment process. The site is also added to federal active CERCLIS site inventory. Next, the EPA, its state and tribal partners, or the appropriate federal

department or agency conduct a preliminary assessment. If needed, a site inspection or other more in-depth assessment is conducted to determine whether a site warrants short- or long-term cleanup attention. If the site does not require further attention, it is designated as “no further remedial action planned” (NFRAP). Sites requiring further study are referred to appropriate cleanup programs, which may include EPA’s Emergency Response and Removal program, EPA’s RCRA Corrective Action program, state and tribal cleanup initiatives, such as voluntary cleanup programs (VCPs), the Superfund Alternative Approach (SAA), and the NPL. Finally, the HRS model is applied to derive a preliminary site HRS score. Sites with preliminary HRS scores below 28.5 generally require no further Superfund remedial interest and are

assigned a NFRAP decision. The NFRAP decision can also be made at sites with preliminary HRS scores of 28.5 or higher if EPA determines the site would receive a “no action” Record of Decision (ROD) if placed on the NPL. Most sites assessed for potential NPL listing are screened out of the program.

Cleaning up abandoned disposal sites involves isolating and containing contaminated material, removing and redepositing contaminated sediments, and in situ and direct treatment of the hazardous wastes involved. The same physical, chemical, and biological treatment technologies discussed previously are applied to remediating abandoned sites.

4.1 Ex Situ and In Situ Treatment

Contaminated soil and sediment must often be removed and treated off-site (*ex-situ*). Contaminated soil may be excavated and transported to kilns or other high-temperature operations, where the contaminated soil is mixed with combustible material. High-sand-content soils may be used as part of an asphalt mix. Contaminated soil may also be distributed onto an impermeable surface, allowing the more volatile compounds to evaporate. Microbial biodegradation can be accelerated and enhanced by adding nutrients and moisture to the soil. A faster process, thermal desorption, entails heating the soil to evaporate the contaminants and capture the compounds, and then burn them in a vapor treatment device.

Groundwater generally is treated by drilling recovery wells to pump contaminated water to the surface. Commonly used groundwater treatment approaches include air stripping, filtering with granulated activated carbon (GAC), and air sparging. Air stripping transfers volatile compounds from water to air. Groundwater is allowed to drip downward in a tower filled with a permeable material through which a stream of air flows upward. Another method bubbles pressurized air through contaminated water in

a tank. Filtering groundwater with GAC entails pumping the water through the GAC to trap the contaminants. In air sparging, air is pumped into the groundwater to aerate the water. Most often, a soil venting system is combined with an air sparging system for vapor extraction.

Hazardous wastes treated where they are found without first removing them is known as in situ remediation. Bioremediation makes use of living microorganisms to break down toxic chemicals or to render them less hazardous. This is often done by using bacteria, and in some instances algae and fungi, that are already living in the soil, sediment, or water. These microbes are exposed to incrementally increasing amounts of the chemical, so that they adapt to using the chemical as an energy (food) source. This process is known as acclimation. The acclimated microbes can then be taken from the laboratory and applied to the waste in the field. The most passive form of bioremediation is natural attenuation, where no direct engineering intervention is used, and the contaminants are allowed to be degraded by resident microbes over time. The only role for the engineer is to monitor the soil and groundwater to measure the rate at which the chemicals are degrading. Natural attenuation can work well for compounds that are found in the laboratory to break down under the conditions found at the site. For example, if a compound is degraded under reduced, low pH conditions in the laboratory, it may also degrade readily in soils with these same conditions (e.g., in deeper soil layers where bacteria have adapted to these conditions naturally). Natural attenuation can sometimes be enhanced, for example, when soil moisture levels are increased.

In situ treatment can be a combination of numerous technologies. For example, the leachate collection systems of a hazardous waste landfill need to be treated provide a way to collect wastes that can then be treated. This is often via “pump-and-treat” systems can produce air pollutants that must be controlled (see [Fig. 31.17](#)). Leachate and

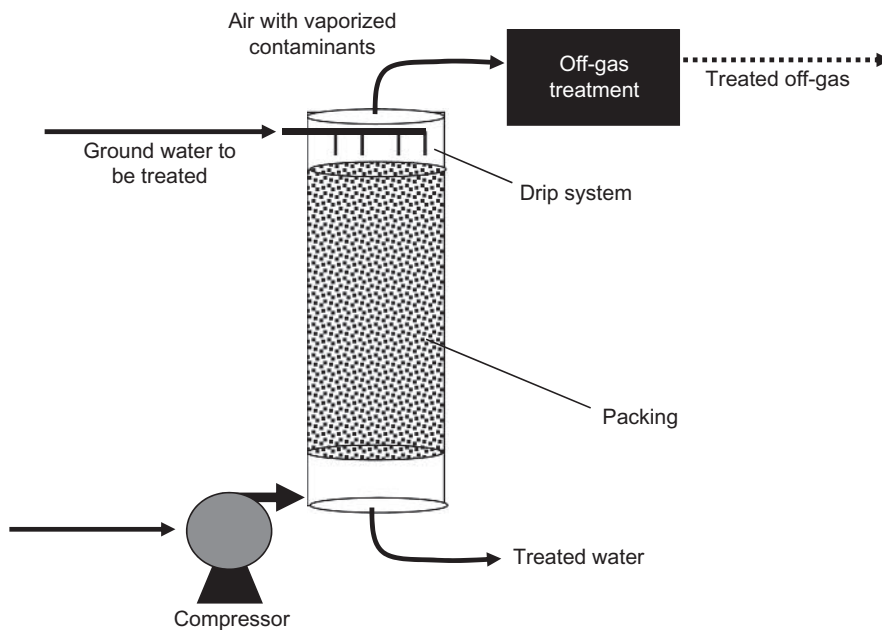


FIG. 31.17 Schematic diagram of air stripping system to treat volatile compounds in water.

groundwater can be treated by drilling recovery wells to pump contaminated groundwater to the surface. Commonly used groundwater treatment approaches include air stripping, filtering with granulated activated carbon (GAC), and air sparging. Air stripping transfers volatile compounds from water to air (Fig. 31.17).

During one air stripping configuration, groundwater drips downward in a tower filled with a permeable material through which a stream of air flows upward. Another method bubbles pressurized air through contaminated water in a tank. The air leaving the tank (i.e., the off-gas) is treated by removing vapor phase pollutants. Filtering groundwater with GAC entails pumping the water through the GAC to trap the contaminants. In air sparging, air is pumped into the groundwater to aerate the water. Usually, a soil venting system is combined with an air sparging system for vapor extraction, with the gaseous pollutants treated, as in air stripping.

Certainly, microbial activity can even enhance the treatment of vapor phase compounds, for example, the volatile organic compounds (VOCs) like benzene, vinyl chloride, and acrolein (propenal), in wastes. In any biological system, biofilms of microorganisms (bacteria and fungi) are grown on porous media. The air or other gas containing the VOCs is passed through the biologically active media, where the microbes break down the compounds to simpler compounds, eventually to carbon dioxide (if aerobic), methane (if anaerobic), and water. The major difference between biofiltration and trickling systems is how the liquid interfaces with the microbes. The liquid phase is stationary in a biofilter (see Fig. 31.18), but liquids move through the porous media of the system, that is, the liquid “trickles” as it does in Fig. 31.17. Compost can be used as the biofiltration system’s porous media (see Fig. 31.19). Compost contains numerous species of beneficial microbes that are already acclimated to organic wastes. Industrial compost biofilters have achieved removal rates

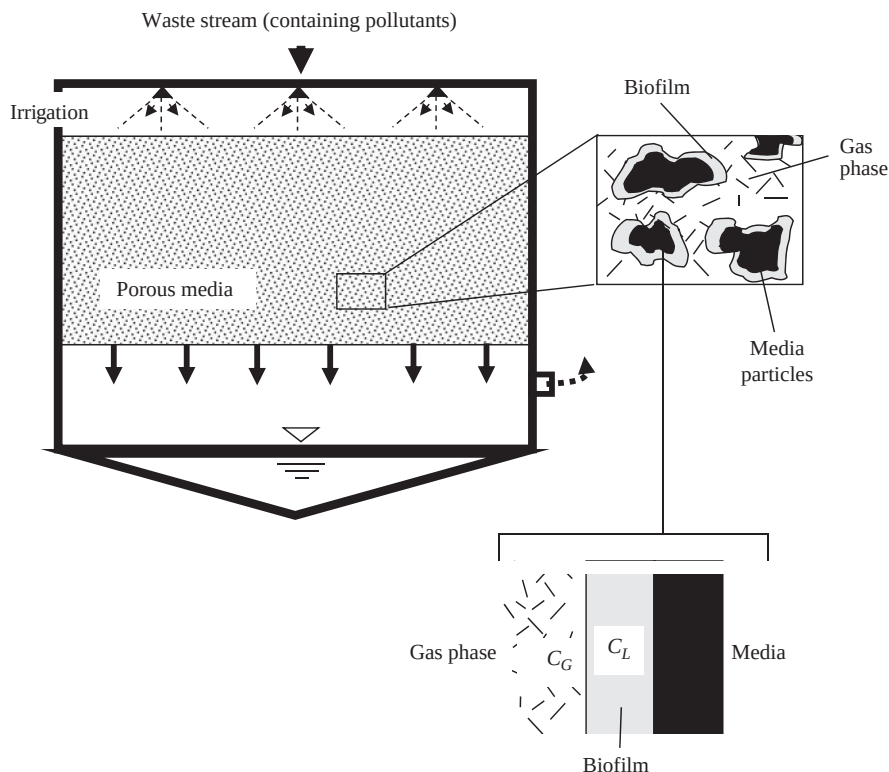


FIG. 31.18 Schematic of packed bed biological control system to treat volatile compounds. Air containing gas phase pollutants (C_G) traverse porous media. The soluble fraction of the volatilized compounds in the air stream partition into the biofilm (C_L) according to Henry's Law: $C_L = \frac{C_G}{H}$, where H is the Henry's Law constant. Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999; adapted from S.J. Ergas, K.A. Kinney, *Biological control systems*, in: *Air Pollution Engineering Manual*, 2000, p. 55.

at the 99% level. Biofilters are also the most common method for removing VOCs and odorous compounds from air streams.

Treatment effectiveness is highly dependent on the degradability of the compounds present in the air stream, their fugacity and solubility needed to enter the biofilm, and pollutant loading rates. Care must be taken in monitoring the porous media to determine the presence and extent of problems, especially incomplete biodegradation, the presence of substances that may be toxic to the microbes, excessive concentrations of organic acids and alcohols, and excessively high or low pH. The system should also be checked for shock and the presence of dust,

grease, or other substances that may clog the pore spaces of the media [12].

4.2 Phytoremediation

Plants are also used in hazardous waste cleanup. Phytoremediation is bioremediation by way of plant life. It is usually in situ and is almost always dependent of available air, that is, higher order plants are exclusively aerobic.

Phytoremediation takes advantage of plants' absorption of CO_2 for photosynthesis, the process whereby plants convert solar energy into biomass and release O_2 as a by-product. Thus the essential oxygen is actually the waste

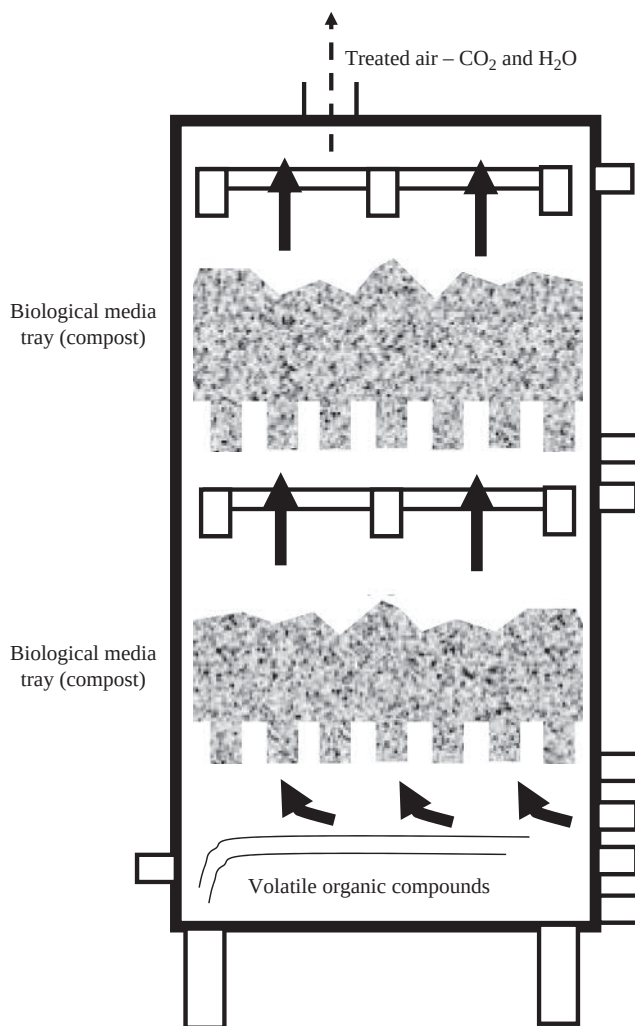


FIG. 31.19 Biofiltration without a liquid phase used to treat vapor phase pollutants. Air carrying the volatilized contaminants upward through porous media (e.g., compost) containing microbes acclimated to break down the particular contaminants. The wastes at the bottom of the system can be heated to increase the partitioning to the gas phase. Microbes in the biofilm surrounding each individual compost particle metabolize the contaminants into simpler compounds, eventually converting them into carbon dioxide and water vapor. Source: D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, p. 999.

product of photosynthesis and is derived from carbon-based compounds. Respiration generates carbon dioxide as a waste product of oxidation that takes place in organisms, so there is a balance between green plants' uptake of CO_2 and release of O_2 in photosynthesis and the uptake of O_2 and release of CO_2 in respiration by animals, microbes, and other organisms.

Phytoremediation [28] can be used for a wide range of contaminants and soil types. It is frequently used to remediate metal-contaminated

sites (e.g., nickel and its compounds). Phytoextraction (or phytoaccumulation) involves the uptake of contaminants from soil by roots into the transfer, that is, translocation, to above-ground portions of the plants. Various species of plants, depending on the contaminant, soil, climate, and local conditions are planted and grown. Some are harvested like crops (e.g., grasses) and others maintained for removal and sequestration of the contaminants for longer time periods. The harvested materials can be treated

and recycled by various methods, including composting and other bioremediation approaches and thermal processes, depending on the sequestered pollutants (e.g., content and form of halogenated and metallic compounds) or recycling of the metals. This procedure may be repeated as necessary to decrease soil contaminant levels down to target cleanup concentrations. If thermally treated, all emissions and ash residues must meet regulatory requirements, including disposal as a possible hazardous waste.

Nickel, zinc, and copper are metals that have been particularly amenable to phytoextraction since hundreds of plant species have mechanisms for their uptake and absorption. This would seem to indicate numerous other metals would be also be candidates since the micronutrient cycling and translocation mechanisms may be similar.

Rhizofiltration (rhizo-root) is the adsorption or precipitation of dissolved compounds onto plant roots or absorption into the roots. Rhizofiltration usually addresses contaminated groundwater, while phytoextraction targets contaminated soil. Thus the plants are usually grown hypoponically in greenhouses and exposed to water from the contaminated site once the plants grow mature root systems. This acclimation step allows the plant's endogenous processes to become acclimated to the chemicals in the water. After acclimation, the plants are transplanted in soil above the contaminated aquifer or perched water table, and when their uptake is considered to have reached a threshold they are harvested and the biomass treated similarly to those from phytoextraction.

Phytostabilization immobilizes contaminants in the soil and groundwater by sorption and accumulation by roots, by adsorption onto roots, or by precipitation within the root zone of plants (rhizosphere). The biochemodynamics hinder transport, for example, to the groundwater or air, as well as decreasing bioavailability of the contaminants.

In addition to these physical translocation and filtering processes, plants can degrade pollutants, using mechanisms similar to microbial degradation. Phytodegradation or phytotransformation is the process of degrading compounds after uptake by the plant's metabolism. It may also involve the breakdown of compounds externally by exogenous secretions, such as enzymes. Complex organic molecules follow similar degradation pathways to those of microbes, discussed in this chapter. The metabolism breaks complex molecules into simpler compounds to gain energy and to build plant biomass, catabolism, and anabolism, respectively.

Rhizodegradation goes by a number of names, including enhanced rhizosphere biodegradation, phytostimulation, and planted-assisted bioremediation/degradation is actually the same microbial process as those described earlier in this chapter, that is, the degradation results from microbes using the contaminants as their energy and carbon sources. Microbes degrade soil-borne contaminants microbially, but these mechanisms are enhanced by the biochemodynamics of the root zone (the rhizosphere). This process is slower usually than phytodegradation. This process can enhance cometabolism because plant roots release natural substances, for example, sugars, alcohols, and acid, that are food for soil microorganisms. The fixation and release of nutrients are also a natural type of biostimulation for the microbes. In addition, the roots provide conduits and physical loosening of soil, improving microbial contact with oxygen and nutrients—both a transport and transformation process. A plant takes up a compound from the soil or aquifer and transpires it to the troposphere. This can be solely the parent compound, if it resists degradation, that is, metabolism and growth products, or it may be the metabolic degradation products, or both. For example, a poplar may volatilize as much as 90% of the volatile organic compound taken up by the tree.

In reality, both microbial and macrophytic processes occur simultaneously. Phytoremediation has been used successfully on a variety of compounds in numerous locations. The local conditions and properties of the contaminants determine the degree of degradation. The waste manager should consult resource guides for more information [29, 30].

The harvested plants will contain elevated concentrations of compounds that have not degraded, especially metals. Thus care must be taken in handling these plants, which must be treated on-site or transferred to a treatment facility.

5 CONCLUSIONS

Hazardous wastes exist in various forms. A wide range of methods are available for treating substances after they have been released into the environment. The waste manager must take great care in selecting, designing, operating, and maintaining systems to collect, transport, store, and dispose of hazardous wastes. Eliminating the wastes before they are released is the best hazardous waste approach. Otherwise, treatment technologies will have to be used to reduce the volume and toxicity of wastes, thereby reducing the hazards and the associated risks.

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Land Pollution

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1 INTRODUCTION

There are three basic types of environmental stressors: physical, chemical, and biological. For land, the two major types are chemical and physical. Land is susceptible to pollution in two basic ways. It can be contaminated by chemical pollutants or it can be altered physically in a manner that renders it less useful or sustainable. All of the wastes discussed in this book have a spatial profile, that is, they are distributed in

two dimensions across the globe. Waste management always involves land, whether a straightforward calculation of the hectares needed for a landfill to handle a town's solid waste for the next 25 years or ways to prevent the loss of prime farmland, or ways to cleanup an abandoned waste site. Indeed, the waste manager must participate in addressing all of these challenges and more.

Environmental planners, scientists, and engineers have noted with some consternation,

especially for the past 70 years [1, 2], that land is often treated as a blank medium on which architects and engineers compose their designs and where governments, developers, and construction companies reshape it to meet societal wants and needs. Certainly these human choices are important. People need housing, roads, and infrastructure, but land is more than this *tabula rasa*. It is a living system that performs countless services that are often shrouded. Thus there is a need to consider the special challenges in protecting land from the various wastes that find their way onto the land and that displace the land's many values.

Previous chapters have discussed how soil and water become contaminated by the chemical constituents of wastes, such as leachate from landfills, hazardous waste storage and treatment facilities, and even from atmospheric pollutants, for example, sulfur and nitrogen compounds that lead to acid rain. This is certainly an important kind of land pollution, but not the only type. This chapter takes an inclusive approach to land waste. It focuses on how land can be harmed by human activities, such as construction, agriculture, and transportation. These and other human activities lead to the release of chemical contaminants, but they also result in landscape damage, such as soil erosion, habitat destruction and loss of resources, such as wetlands and coastal ecosystems. This chapter also considers ways to ameliorate damage to land caused by human activities that leave wastes behind in different locations.

2 THE LAND ETHIC

A full accounting of the value of a land must include cultural and social factors. In fact, environmental impact statements (EISs) under the National Environmental Policy Act (NEPA) require that these factors be part of the decision as to whether a federal project would have a significant effect on the environment. These

included historic preservation, economics, psychology (e.g., open space, green areas, and crowding), esthetics, urban renewal, and the so-called land ethic. Aldo Leopold in his famous essays, posthumously published as *A Sand County Almanac*, argued for a holistic approach toward land:

A thing is right when it tends to preserve the integrity, stability and of the biotic community. It is wrong when it tends otherwise. [3]

NEPA was in many ways symbolic of the new federal commitment to environmental stewardship and a template for proper land development. It was signed into law in 1970 after contentious hearings in the U.S. Congress. NEPA was not really a technical law. It did two main things. In addition to requiring EISs, it established the Council on Environmental Quality (CEQ) in the Office of the President. Of the two, the EIS represented a sea change in how the federal government was to conduct business. Agencies were required to prepare EISs on any major action that they were considering that could "significantly" affect the quality of the environment. From the outset, the agencies had to reconcile often-competing values, that is, their mission and the protection of the environment.

The CEQ was charged with developing guidance for all federal agencies on NEPA compliance, especially when and how to prepare an EIS. The EIS process combines scientific assessment with public review. The process is similar for most federal agencies. Agencies often strive to receive a so-called finding of no significant impact (FONSI), so that they may proceed unencumbered on a mission-oriented project. This is understandable if the agency is in the business of something not directly related to environmental and waste management, but it is not unusual for even the natural resources and environmental agencies to assert that there is no significant impact to their projects. It causes the cynic to ask, then, why are they engaged in any project

that has no significant impact? The answer is that the term “significant impact” is really understood to mean “significant adverse impact” to the human environment. Those agencies with environmental charters are more likely to assert that their missions are generally enhancers of environmental quality. This may be true, but even a mission of enhancement can have pockets of detriment. For example, an agency that funds landfills may for the most part improve the environment by properly handling potential contamination, but may also

harm parts of the environment due to improper siting, which causes undue problems for certain segments of society, for example, lower socioeconomic sectors whose home values are adversely affected [4–6].

It is tempting to think that land is a “blank slate” or that buildings are simply three-dimensional structures ready to be built, changed, or demolished as means to engineering ends. In fact, land and structures are human enterprises that will affect people’s lives directly—See [Discussion Box 32.1](#).

DISCUSSION BOX 32.1 FAILURES IN LAND DEVELOPMENT: THE CASE OF PRUITT-IGOE

Regrettably, it is not difficult to find ample examples of improper development of land and other wastes, no matter where one resides. Land waste can result from subdivisions with improper erosion and sediment control systems, clear-cutting trees and complete disregard for and elimination of sensitive ecosystems, as discussed later in this Chapter. Another type of improper land development has to do with social values. The Pruitt-Igoe public housing project provides an example of failing to include land as an application of the social sciences in planning, design, construction, and maintenance. This housing development in St. Louis, Missouri was supposed to be emblematic of advances in fair housing and progress in the war on poverty. Instead, Pruitt-Igoe has become an icon of failure of imagination, especially imagination that properly accounts for the human condition. Although we think of public housing projects in terms of housing, they also often represent elements of environmental justice. Contemporary understanding of environmental quality is often associated with physical, chemical, and biological contaminants, but in the formative years of the environmental movement, esthetics and other

“quality of life” considerations were essential parts of environmental quality.

The project was designed before EISs and the land ethic was yet to be articulated prior to the construction of the Pruitt Igoe project, so the designers did not benefit from the insights of Leopold and his contemporaries. However, the problems that led to the premature demolition of this costly housing experiment may have been anticipated intuitively if the designers had taken the time to understand what people expected.

In such catastrophic failure, there is usually plenty of culpability to go around. Some blame the inability of the modern architectural style to create livable environments for people living in poverty, largely because they “are not the nuanced and sophisticated ‘readers’ of architectural space the educated architects were.” [7] This is a telling observation and an important lesson for anyone developing land. We need to make sure that the use and operation of whatever is designed is sufficiently understood by those living with it, long after the designers have left.

Design incompatibility was almost inevitable for high rise buildings and low-income families with children. It appears that socioeconomics

Continued

DISCUSSION BOX 32.1 FAILURES IN LAND DEVELOPMENT: THE CASE OF PRUITT-IGOE *(cont'd)*

play a large role in the success of housing developments. Most large cities have large populations of families with children living in such environments. Indeed, St. Louis had successful luxury townhomes not too far from Pruitt Igoe, with many of the same design features. Part of the problem can be traced to racism in the era when the project was conceived. In fact, when originally inhabited the Pruitt section restricted to African-Americans and Igoe to whites.

Costs always become a factor in land waste. The building contractors' bids in the Pruitt-Igoe project were increased to a level where the project construction costs in St. Louis exceeded the national average by 60%. The response to the local housing authority's refusal to raise unit cost ceilings to accommodate the elevated bids was to reduce room sizes, eliminate amenities, and raise densities [8]. As originally designed, the buildings were to become "vertical neighborhoods" with nearby playgrounds, open air hallways, porches, laundries, and storage areas. The compromises eliminated these features. And, some of the removal of "amenities" led to dangerous situations. Elevators were undersized and stopped only every third floor and lighting was

inadequate in the stairwells. So, another lesson must be to know the difference between desirable and essential design elements. No self-respecting structural engineer involved in the building design would have shortcut the factors of safety built into load bearing. Conversely, human elements essential to a vibrant community were eliminated without much if any accommodation [9].

Finally, the project was mismatched to the people who would live there. Many came from single family residences. They were moved to a very large, imposing project with 2800 units and almost 11,000 people living there. This was quadrupled the size of the next largest project of the time.

When the failure of the project became overwhelmingly clear, the only reasonable decision was to demolish it, and this spectacular implosion became a lesson in failure for planners, architects, and engineers. In the designer, Yamaski's own words:

I never thought people were that destructive. As an architect, I doubt if I would think about it now. I suppose we should have quit the job. It's a job I wish I hadn't done [9].

3 THE COMPLAINT PARADIGM

In many places, environmental response is often precipitated first by a complaint. The underlying assumption of fairness is that every not only has a voice in the process, but that that voice is loud enough to be heard. However, if a certain group of people has had little or no voice in the past, they are likely to feel and be disenfranchised. For example, for centuries African-American communities were not successful in voicing concerns about environmentally unacceptable conditions in their neighborhoods. Presently, Hispanic-

Americans may have even less voice in environmental and public health matters since the government may not be seen as a viable place to lodge a complaint and the perceived risks of complaining (e.g., questions about citizenship and possible deportation) may outweigh the expected benefit (e.g., cleaner environment).

Aldo Leopold's "land ethic" is a reminder that the use of land is dependent on the values placed on it. One means of determining land's value is a scientific tabulation of the land's resources and threats to those resources. Since NEPA's passage (see [Chapter 3](#)), land use

decisions in the United States must follow from an environmental assessment. Most environmental impact assessment handbooks prior to the late 1990s contained little information and guidelines related to fairness issues in terms of housing and development. They were usually concerned about open space, wetland and farmland preservation, housing density, ratios of single versus multiple family residences, owner occupied housing versus rental housing, building height, signage and other restrictions, designated land for public facilities like landfills and treatment works, and institutional land uses for religious, health care, police, and fire protection.

When land uses evolve (usually to become more urbanized), the environmental impacts may be direct or indirect. Examples of direct land use effects include *eminent domain*, which allows land to be taken with just compensation for the public good. Easements are another direct form of land use impacts, such as a 100-m right-of-way for a highway project that converts any existing land use (e.g., farming, housing, or commercial enterprises) to a transportation use. Land use change may also come about indirectly, such as so-called secondary effects of a project that extend, in time and space, the influence of a project. For example, a wastewater treatment plant and its connected sewer lines will create accessibility which spawns suburban growth [10]. People living in very expensive homes may not even realize that their building lots were once farmland or open space and, had it not been for some expenditure of public funds and the use of public powers like eminent domain, there would be no subdivision.

3.1 Competing Values: Affordable Housing Versus Conservation

Environmentalists are generally concerned about increased population densities, but housing advocates may be concerned that once the land use has been changed, environmental and

zoning regulations may work against affordable housing. Even worse, environmental protection can be used as an excuse for some elitist and exclusionary decisions. In the name of environmental protection, certain classes of people are economically restricted from living in certain areas. This problem first appeared in the United States in the 1960s and 1970s in a search for ways to preserve open spaces and green areas. One measure was the minimum lot size. The idea was that rather than having the public sector securing land through easements or outright purchases (i.e., fee simple) to preserve open spaces, developers could either set aside open areas or require large lots in order to have their subdivisions approved. Thus green areas would exist without the requisite costs and operation and maintenance (O&M) entailed by public parks and recreational areas. Such areas have numerous environmental benefits such as wetland protection, flood management, and esthetic appeal. However, minimum lot size translates into higher costs for residences. The local rules for large lots that result in less affordable housing is called *exclusionary zoning*. One value (open space and green areas) is pitted against another (affordable housing). In some cases, it could be argued that preserving open spaces is simply a tool for excluding people of lesser means or even people of minority races [11].

Land use plans must somehow balance the need to preserve economic value of homes and to enhance the quality of our neighborhoods with fair and affordable housing. Thus engineers and land use planners must take great care that their ends (environmental protection) are not used as a rationale for unjust means (unfair development practices). Environmental laws and policies, like zoning ordinances and subdivision regulations, should not be used as a means to keep lower socioeconomic groups out of privileged neighborhoods.

Environmental quality continues to be used, knowingly or innocently, to compete with

fairness. This may be most dramatically demonstrated when people who benefit little bear too large a burden in terms of pollution and waste. Often, exposures to the hazards brought about by land use decisions are set in place well before the actual land use decisions are made. In fact, since everything engineers do may have an impact on health, safety, and welfare, inclusiveness and affordability should be factors in all standard operating procedures for all designs that potentially affect the public. Engineers and planners must find ways to ensure plans are fair and just, often looking beyond property value “bottom lines.” Sustainable development, therefore, is the result of applications of both physical and social sciences.

Environmental injustice can result from factors other than the profit motive and its driving corporate decisions to site environmentally hazardous facilities where people are less likely to complain. Public decisions have also brought lower socioeconomic communities into environmental harms way. Although public agencies, such as housing authorities and public works administrations do not have a profit motive, *per se*, they do need to address budgetary and policy considerations. If open space is cheaper and certain neighborhoods are less likely to complain (or by extension, vote against elected officials) the “default” for unpopular facilities such as landfills and hazardous waste sites may be to locate them in lower income neighborhoods.

It may be easier to site other types of unpopular projects, such as public housing projects, in areas where complaints are less likely to be put forth or where land is cheaper. In 1954, for example, the Dallas, Texas, Housing Authority built a large public housing project on land immediately adjacent to a lead smelter. The project had 3500 living units and became a predominantly African-American community. During the 1960s the lead smelter stacks emitted over 200 t of lead annually into the air. Recycling companies had owned and operated the smelter to recover lead from as many as 10,000 car batteries

per day. The lead emissions were associated with blood lead levels in the housing project’s children and these were 35% higher than in children from comparable areas.

Lead is a particularly insidious pollutant because it can result in developmental damage. Study after study showed that the children at this project were in danger of higher lead levels, but nothing was done for over 20 years. Finally, in the early 1980s, the city brought suit against the lead smelter, and the smelter immediately initiated control measures that reduced its emissions to allowable standards. The smelter also agreed to clean up the contaminated soil around the smelter and to pay compensation to people who had been harmed.

This case illustrates two issues of environmental racism and injustice. First, the housing units should never have been built next to a lead smelter. The reason for locating the units there would have been justified on the basis of economics. The land was inexpensive and thus this saved the government money. The second issue was delays by the city in insisting that the smelter clean up the emissions. Once the case had been made, within 2 years the plant was in compliance. By 2003, blood lead levels in West Dallas were below the national average. Thus time is often of the essence in land use decisions.

4 ADDRESSING LAND POLLUTION

Local governments address land pollution using a number of tools, including land use plans, zoning ordinances, and development rules, such as subdivision regulations, which must undergo significant public review. An illustrative example is that of Durham, NC. The City of Durham Public Works mission statement is based on the City of Durham’s *Customer Bill of Rights*, which is a citizen-focused initiative to ensure that the city’s residents receive excellent service according to their land use and environmental needs and expectations [12]. Like many other local communities, human health and environmental quality

are top priorities in fulfilling the city's mission. The chief instrument in the environmentally responsible approach is achieved by the city's growth adhering to the *Unified Development Ordinance*, which is designed to promote the health, safety, and general welfare of the residents of Durham City and County. It does so by:

- A. Protecting existing neighborhoods, preventing their decline and promoting their livability;
- B. Addressing future needs, growth, and change in the jurisdiction;
- C. Conserving land and water resources;
- D. Preserving groundwater quality and supply;
- E. Recognizing geologic features, soil and topography;
- F. Improving air quality;
- G. Minimizing congestion in the streets and reduce reliance on automobiles by providing options for walking, bicycling, and transit use;
- H. Securing safety from fire and other dangers;
- I. Providing adequate light and air;
- J. Preventing overcrowding of land and undue concentrations of population;
- K. Providing adequate transportation, water supplies, sewer service, schools, parks, open space, and public facilities;
- L. Conserving the value of buildings;
- M. Examining the most appropriate use of the land;
- N. Regulating the location of business and industry;
- O. Regulating the height and bulk of buildings;
- P. Protecting the capacity of floodways and nonencroachment areas in order to prevent loss or damage to homes or property;
- Q. Regulating the area of yards and open spaces for buildings;
- R. Providing for the needs of agriculture;
- S. Protecting historic sites and areas;
- T. Encouraging an esthetically attractive community; and

- U. Preventing secondary effects from land uses that could negatively impact nearby land uses, consistent with prior ordinances restricting such uses and evidence supporting such restrictions.

This list of expectations provides a waste manager and engineer with a yardstick for land use. If an activity adheres to all of these factors, it is likely to be acceptable environmentally. The ordinance provides for the orderly, efficient, and economic development of the City and County by coordinating streets, highways, and other public facilities within proposed subdivisions with existing or planned streets and highways or other public facilities. It also provides for the dedication and reservation of rights-of-way, easements or sites for streets, utilities, open space, recreation areas, and other public facilities, the protection of historic resources and the natural environment; and the distribution of population and traffic to avoid congestion and overcrowding and which shall create conditions essential to public health, safety, and the general welfare.

5 CHARACTERIZING LAND POLLUTION

A key indicator of land pollution is the amount of pollution exchanged between land and water systems. These can be natural, for example, land uses near a river, or human-induced, for example, catchment basins and sedimentation ponds in a subdivision. Land and water are intricately connected. In addition to the damage caused to the land when topsoil is lost after a precipitation event, the stormwater transports both suspended material (e.g., soil, debris) and soluble matter (e.g., organic and organic chemicals). These materials either directly enter surface waters or reach a storm sewer system. The material reaching the water is harmful in two ways. First, it harms the integrity of the receiving stream, increasing turbidity, suspended and dissolved solids content, and increases the organic load. Second, the material can be hazardous.

The material in the runoff is collectively referred to as “sediment,” which can substantially decrease the ability of light to penetrate the water column, that is, increased turbidity. Sediment loading diminishes the growth capacity of aquatic plants and disrupts normal processes, such as seasonal turnover and nutrient cycling in the surface waters.

Household hazardous wastes, such as insecticides, pesticides, paint, solvents, used motor oil, and other auto fluids are also frequently part of the sediment load. These are often highly toxic to aquatic life and human populations. These wastes are discussed in detail in [Chapter 17](#). In addition, pathogenic microbes suspended or sorbed to suspended particles can cause major health problems and indicate the presence of enteric bacteria (see [Chapter 8](#)). Such land-water problems can result from both agricultural and human waste sources, for example, septic tanks or even poorly treated effluent from municipal waste water treatment systems. They may also be exacerbated by natural events, such as floods and hurricanes that increase the waste loads and overrun engineered systems that are no longer able to prevent the connection between the waste source and human populations.

Waste managers may also protect land integrity by pollution prevention and control. For example, land can become littered by debris leaving landfills and waste disposal facilities. Toxic substances that are released from waste processing and treatment facilities, for example, incinerators, can spread toxic metals and persistent organic pollutants from stack and vent plumes. The deposition of these contaminants can render land useless and increase toxic exposures, such as by the translocation of toxic metals to fruit and vegetables in gardens and fields (see [Fig. 32.1](#)).

5.1 Point and Nonpoint Sources of Land Pollution

The amount of any substance (e.g., nutrient, pollutant or microbes) that is discharged into a system is known as the *load*. Nutrient loading, pollutant loading, and microorganism loading can be quantified, not only by the gross mass of the substance entering a system, for example, a water body, but also by the response of that system to the load. Thus this is a quantification of the relationship between a substance’s entry and its impact on the receiving river, lake, wetland, estuary, ocean, or aquifer. However, these

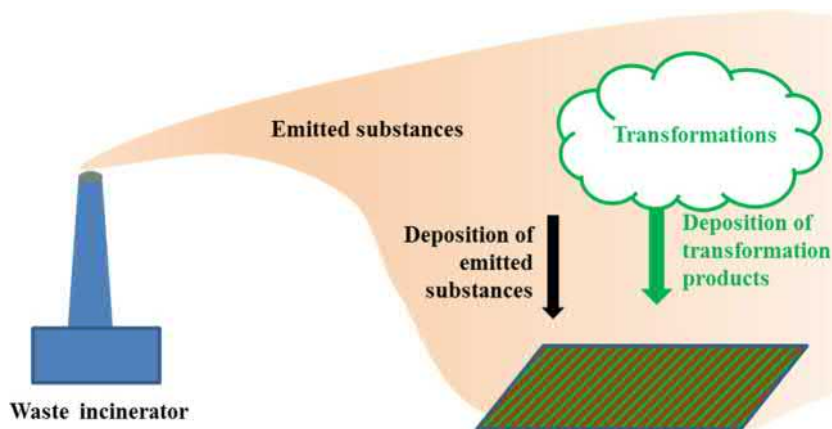


FIG. 32.1 Example of indirect land contamination from waste handling by incineration. The plume from an incinerator of both parent chemical compounds emitted and transformation products, for example, from photolytic and hydrolytic reactions. Some of these compounds are deposited on soil and plants in gardens and fields, where the chemicals may be taken up and accumulate in edible parts of these plants.

receptors can also be compartmentalized into their various media, for example, soil, sediment, water, and biota.

The first major division of loads is between *point sources* and *nonpoint sources*. This is actually a distinction of convenience. What some may call a point source, others may consider it to be a nonpoint source. For example, if a 1-ha field is near a small creek, this may be a relatively large and dispersed source of a pesticide being released to the creek. However, a 1-ha trickling filter system near a large river may be classified as a point source since the majority of the discharge to the river comes through a conduit (i.e., the *outfall structure*) from the system. However, it is highly likely that pollutants are being released from the treatment facility from sources other than the outfall structure.

Thus nonpoint sources are generally associated with *runoff*, that is, multiple sources in a given two-dimensional space that leave these sources and are transported toward a receptor system. These receiving bodies can be above ground (e.g., streams and lakes) or below ground (aquifers). They are usually cascades of systems, such as a contaminant moving atop the soil, with some infiltration. The infiltrated fraction may find its way to the aquifer and moves much more slowly than the runoff above the ground. However, the contaminated ground water may recharge a stream flow. The same stream may have already been contaminated by the overland flow, so the stream is receiving a continuous flow (ground water source to stream) and a plug or episodic flow (overland runoff), as shown in Fig. 32.2.

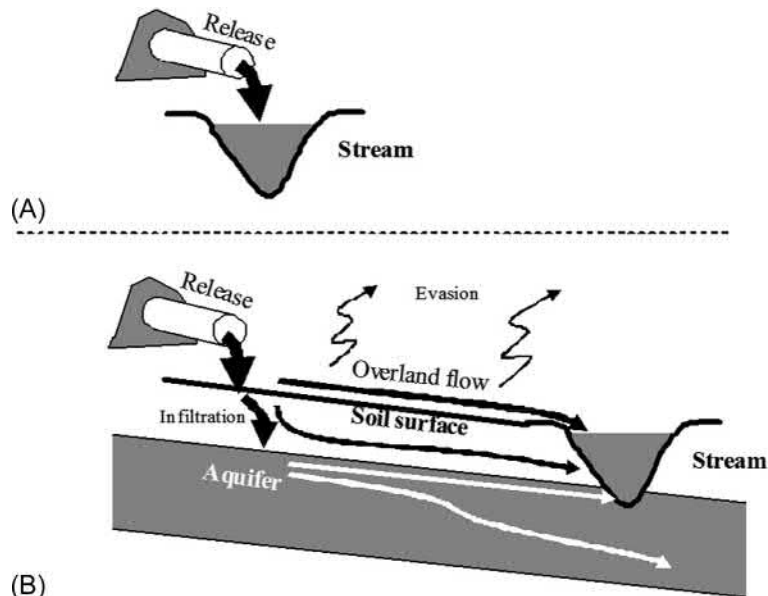


FIG. 32.2 (A) Point source—material is released directly the receiving body. (B) Nonpoint source—material runs off, infiltrates through soil column, follows ground water flow lines, and eventually reaches the receiving body. However, along the way, a fraction of the material may be chemically transformed and physically held (e.g., sorbed to soil particles). For volatile compounds, a fraction will also be evaded to the atmosphere. Thus the net the reaching the water body is a function of numerous factors, including vegetative cover, soil porosity and permeability, ground water flow rates, soil texture, and Henry's Law and other equilibrium coefficients for the released material. Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Academic Press, 2010.

For biota, especially bacteria, the nonpoint and point contribution is even more complex than that of chemical compounds. Microbes may be directly loaded into a stream or other receiving body (Fig. 32.2A). In addition, they may accumulate as nonpoint source loads from a combination of sources. As they are transported overland and under the soil surface, the

microbes meet hostile and accommodating conditions, which will decrease and increase their numbers, respectively. However, the hostile conditions may lead to the formation of cysts and spores, which are more likely than the bacteria themselves to be transported by advection in the air and water or carried by fauna (see Fig. 32.3). When the conditions change to

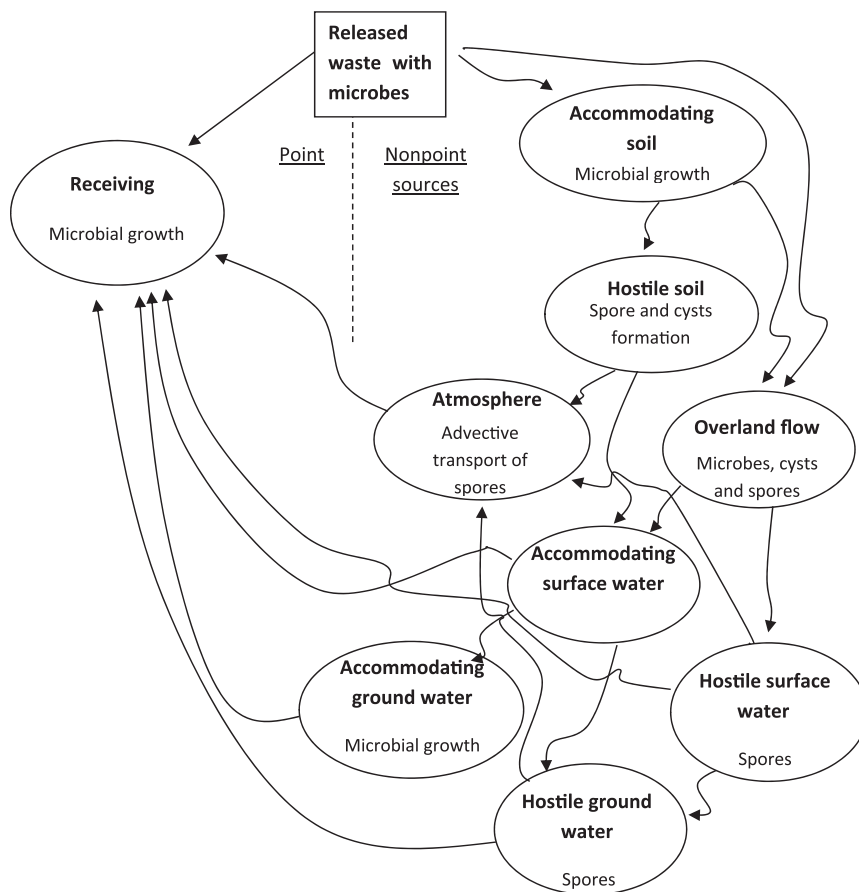
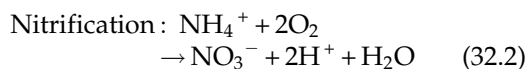
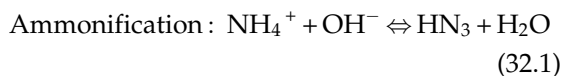


FIG. 32.3 Difference between point source and nonpoint source releases of microbes. In a point source, the growth, metabolism, and formation of cysts and spores depends on the conditions of the receiving water body, which varies with time but not in space. In a nonpoint source scenario, the growth, metabolism, and formation of spores and cysts is a cascade in time and space. In accommodating environments, the microbes will undergo metabolism and growth, which may allow for larger microbial populations delivered to other compartments and eventually to the receiving body. However, various compartments in the flow may be hostile (insufficient nutrients, water, pH, temperature, etc.). These may induce the formation of spores which can be advectively transported in the atmosphere or by with the flow of ground and surface waters. Source: D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Academic Press, 2010.

become more accommodating, the spores will generate increased microbial populations. Thus the actual loading to the body consists of a complicated set of transport and fate processes.

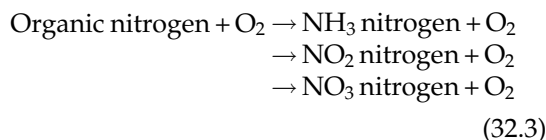
Loading calculations must take into account background sources (sometimes referred to as "natural" sources). Atmospheric loading is similar, but usually the distinctions are made between *mobile sources* and *stationary sources*. Two systems, hydrologic and atmospheric, join at the interfaces between earth and water bodies and the atmospheric, that is, terrestrial and tropospheric fluxes. For example, atmospheric deposition is an important source of nutrient loading (e.g., N, P, S, and K) to ecosystems. Ecosystems, for example, wetlands, load nutrients back into the atmosphere, but often as different chemical species. That is, the ecosystems are acting as control volumes in which reactions are taking place. Many of these reactions are biotic and are mediated by microbes and plants.

The linkages between biota and their environments are influenced by the availability and forms of nutrients. When rain containing nitrates falls to the wetland water and land surfaces, for instance, plant roots take it up and metabolize it into organic forms of nitrogen. Meanwhile, bacteria in sediments reduce it to ammonia. In the opposite direction, the reduced forms are oxidized by other bacteria (e.g., *Nitrosomonas* converts ammonium ions $[\text{NH}_4^+]$ to nitrite $[\text{NO}_2^-]$, *Nitrobacter* converts the NO_2^- to nitrate $[\text{NO}_3^-]$). Thus two opposite reactions are at play constantly in loading scenarios. In this instance, these are *ammonification* (or *deamination*) and *nitrification*:



Note that ammonification is written as an equilibrium reaction, and nitrification is an oxidation reaction. However, the loading depends on

numerous environmental conditions, including pH. Thus under acidic conditions, most of the ammonia nitrogen will ionize to ammonium and under basic conditions the nonionized ammonia concentrations will increase in proportion to the ammonium. This is important since nonionized ammonia is very toxic to aquatic biota, whereas ionized species are nutrients needed for plants and algae. Add to this, the decomposition of organic matter, and the loading becomes a complicated mix of reactions:



Even this is a gross oversimplification, since the oxidation and reduction depends on the types of bacteria present. For example, the O_2 required for nitrification is theoretically.

$4.56 \text{ mg}(\text{O}_2) \text{ mg}^{-2}(\text{NH}_4^+)$, but this is an *autotrophic* reaction. Thus O_2 is being produced by the nitrifying bacteria, decreasing the amount needed. However, the growth rate of nitrifying microbes is far less than that of *heterotrophic* microbes decomposing organic wastes. Therefore when large amounts of organic matter are being degraded, the nitrifiers' growth rate will be sharply limited by the heterotrophs, which means the rate of nitrification will commensurately be decreased [13]. Furthermore, these same responses to conditions exist for all other nutrients in the system, for example, organic P will be oxidized and oxidized P species reduced, etc. Thus the kinetics of nutrient loading are quite complex.

5.2 Total Maximum Daily Loading

In the United States, the Clean Water Act (CWA) restricts the total maximum daily load (TMDL) of pollutants released to water bodies that have been deemed to be *impaired* by the state in which technology-based and other

engineering controls are not adequate to achieve water quality standards. Thus the TMDL reflects the amount of a pollutant that can be discharged from point, nonpoint, and natural background sources, including a margin of safety (MOS) for any water quality-limited water body. The TMDL process consists of five steps:

1. Selection of the pollutant in need of consideration;
2. Estimation of the water body assimilative capacity (i.e., loading capacity);
3. Estimation of the pollutant loading from all sources to the water body;
4. Analysis of current pollutant load and determination of needed reductions to meet assimilative capacity; and,
5. Allocation, including a margin of safety, of the allowable pollutant load among the different pollutant sources in a manner that water quality standards are achieved

A beneficial use that has been impaired is a function of a change in the chemical, physical, or biological integrity of surface waters, such as:

- restrictions on fish and wildlife consumption
- tainting of fish and wildlife flavor
- degradation of fish wildlife populations
- fish tumors or other deformities
- bird or animal deformities or reproduction problems
- degradation of benthos
- restrictions on dredging activities
- eutrophication or undesirable algae
- restrictions on drinking water consumption, or taste and odor problems
- beach closings
- degradation of esthetics
- added costs to agriculture or industry
- degradation of phytoplankton and zooplankton populations
- loss of fish and wildlife habitat.

The general components needed to develop a TMDL are shown in [Fig. 32.4](#). Meeting water

quality standards is a way to protect beneficial uses, including recreational activities, aquatic life, and water supply. For example, recreational beneficial use can be based on protection against fecal coliform, including *Escherichia coli* bacteriological criteria. For example, if a lake is designated for primary contact recreation water, potential exposures to bacteria and a baseline level of disinfection will be required. This can be more straightforward for point sources, for example, building wastewater treatment systems, than for nonpoint sources. The latter often requires management approaches, such as measures to prevent soil erosion since soil may carry coliform bacteria.

6 HABITAT LOSS AND DESTRUCTION

Obvious, terrestrial species depend on both the quantity and quality of land for their survival. In addition, all creatures to some extent are affected by land habitats; some because a life stage is terrestrial, for example, the amphibians, and some because the land is the source of stress on the water (see [Chapter 8](#)).

6.1 Preventing and Enhancing Land Habitats

Plans must include measures that complement the natural and cultural environment and to avoid destruction or adverse alteration of the land. This means that good practice should always consider approaches to minimize impacts of construction, development, and facility operation on the surrounding watershed, by preventing water pollution and actions that disrupt natural drainage patterns.

In addition, land use planning must directly address habitat destruction by recommending ways that any development conserve land that serves as habitat for native flora and fauna, both

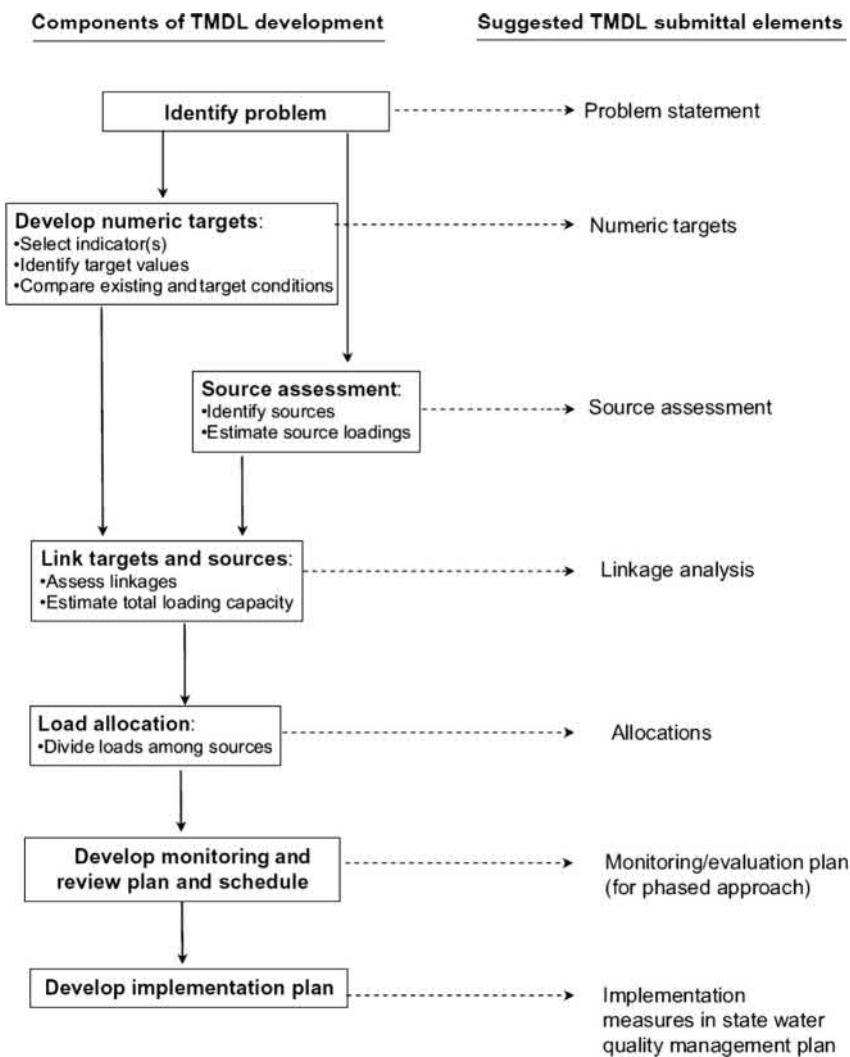


FIG. 32.4 Steps in developing a total maximum daily load. Source: EPA 841-R-00-002, *Protocol for Developing Pathogen TMDLs*, 2001.

on- and off-site, and directly and indirectly. An example of indirect destruction or secondary impacts from infrastructure development is that location of new sewer lines or roads in previously undeveloped or low-density land. This invites new residential and commercial development, which in turn calls for more roads, structures, and impervious surfaces. These

changes then lead to less soil infiltration and increase the risks of flooding on-site and downstream, as the holding capacity for water during rain events decreases.

Another special consideration for land development is the presence of threatened or endangered species, and the potential that their habitats may be affected by developing a site.

7 ENVIRONMENTAL CONTAMINATION OF LAND

Love Canal was the key event that led to the passage of groundbreaking environmental legislation. As mentioned in [Chapter 31](#), in the U.S. Congress passed the Resource Conservation and Recovery Act of 1976 to ensure that wastes are tracked from “cradle to grave” for active hazardous waste facilities, that is, those that are still operational and where an owner/operator is identified [\[14\]](#). The Comprehensive Environmental Response, Compensation and Liability Act of 1980, better known as “Superfund,” was passed to address and clean up abandoned waste sites [\[15, 16\]](#). These laws authorized the thousands of pages of regulations and guidance that declared that when pollution thresholds are crossed, the design has failed to provide adequate protection.

Numerous other waste sites were discovered in the late 1970s, including dioxin contaminated Times Beach, Missouri and abandoned chemicals in the Valley of the Drums, Kentucky. These discoveries prompted regulators to approach pollutants from the perspective of risk.

People living near hazardous waste sites, for good reason, want to be assured that they will be “safe.” But, safety is a relative term. Calling something “safe” integrates a value judgment that is invariably accompanied by uncertainties. The safety of a product or process can be described in objective and quantitative terms. Factors of safety are a part of every waste management decision (see [Chapter 34](#)).

7.1 Restoration of Contaminated Land

A key question when discovering a contaminated site is the extent to which it would be possible to locate and rehabilitate or restore native habitats. For example, the EPA’s Land Revitalization Program has been designed to restore land and other natural resources into

sustainable community assets that maximize beneficial economic, ecological, and social uses and ensure protection of human health and the environment [\[17\]](#).

Projects have included sustainable cleanup and redevelopment, green building, and sustainable development alternatives for affordable housing, incorporating the reuse of construction and demolition debris into redevelopment projects and comprehensive “hands on” training to local government officials on assessing, remediating, and revitalizing contaminated properties in a sustainable manner. When a previously contaminated site is remediated to the point that it has regained a commercial or other beneficial use, this is known as a brownfield. Several sites now exist throughout the United States.

7.2 Brownfield Redevelopment

A brownfield has been broadly defined. For example, the U.S. Environmental Protection Agency (EPA) defines a brownfield as:

... a property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant. It is estimated that there are more than 450,000 brownfields in the U.S. Cleaning up and reinvesting in these properties increases local tax bases, facilitates job growth, utilizes existing infrastructure, takes development pressures off of undeveloped, open land, and both improves and protects the environment. [\[18\]](#)

The size of a brownfield varies. Some activities, like mining, leave a very large footprint of damage. Some of the damage is also transferred away from the mining site, where the ores are processed. Other brownfields are more confined in space, limited to the damage of an abandoned factory, waste site, or warehouse. Of course, upon further scrutiny, the damage may migrate away from the activity site, as pollutants are transported by air and water, above ground and subsurface.

These and other industrial activities can leave zones of contamination, with which local governments and residents must contend. Sometimes, this is a matter of hazardous waste cleanup, as discussed in [Chapters 17, 18, and 31](#), where the government requires that the concentrations of pollutants be reduced to some level, for example, the preindustrial concentrations. There is also a need to focus on how to address contaminated zones more systematically and in ways that lead to a higher use. This goes beyond changing a useless, contaminated site into a useless, uncontaminated site. It is best to convert a contaminated property, that is, a brownfield, into a resource that economic and other uses. The policy makers and waste managers must find ways to return previously contaminated land to usefulness.

The waste manager should expect a very different experience associated with a brownfield redevelopment project from the traditional waste project or hazardous waste cleanup. A redevelopment requires a combination of expertise, including scientific, engineering, legal, and waste management. While these and other expertise are involved in most well-managed waste projects, brownfields often require more intense and extensive input and roles from these groups. This is because the challenges of redevelopment are wide ranging, as are the solutions to these challenges. Some notable considerations before, during, and after a brownfield redevelopment are environmental liability concerns, financial barriers, cleanup considerations, and reuse planning [\[19\]](#).

Developers and property owners must consider ways to manage past and future liabilities associated with the property's environmental history. Actual or perceived legal liability is arguably the most crucial reasons for a private concern's *not* redeveloping a brownfield. Some of the reticence is based on scientific reasoning. For example, the ability to detect chemical compounds continues to improve. A decade ago, a

chemical may have only have been able to have been detected at parts per million, but now can be detected at parts per billion. Thus a redeveloper may fear that a toxic compound that is not detected in soil around an old industrial site today may be detected next year with improved technologies.

Thus there may well be a need to apply legal and engineering fiction to reassure redeveloper would be held harmless. For example, would a reasonable engineer recommend redevelopment, based on best practices and sound science given what is known and should be known about a property? It also requires a level of assurance from insurers and underwriters of what will occur in the event that contamination occurs or is detected in the future. This is an important objective in the Brownfields Amendments to Superfund [\[20\]](#), to provide relief to private sector's "innocent" purchasers from liability, which would otherwise be reluctant to cleanup and reuse brownfields [\[21\]](#). The law also provided financial incentives for such redevelopment. Formerly, Superfund limited liability to "an act of God, an act of war, or an act of a third party" [\[15\]](#).

The 2002 amendments have helped to encourage brownfield redevelopment by limiting liability. The amendments clarified the previous requirement that an innocent property owner respond to even vague and seemingly limitless "all appropriate inquiry," limiting this term to the standards and practices defined in EPA regulations and defined by statutes. The law also stipulates that when selling property the seller disclose actual knowledge of contamination [\[21\]](#). EPA [\[22\]](#) has defined innocent landowners who meet the Superfund criteria and:

persons who can demonstrate, among other requirements, that they "did not know and had no reason to know" prior to purchasing a property that any hazardous substance that is the subject of a release or threatened release was disposed of on, in, or at the property.

Pursuant to the 2002 amendments in the EPA established a performance-based standard in how to conduct searches into previous uses and ownership, as well as in how to inspect the properties. This included the deployment of an “environmental profession” who has sufficient, specific education and experience to determine whether contaminants are being or have been released to the surface or subsurface of the property. These include licensed or registered professional engineers and geologists. The standard also include techniques for interviewing owners and neighbors, reviewing historical and governmental records, conducting inspections, and assessing property value if property were not contaminated [22].

Several other protections have been added to encourage brownfield cleanup and redevelopment, but substantial ambiguities and uncertainties continue to work against redevelopment. Thus waste managers and engineers considering and undergoing brownfield redevelopment should be certain of liabilities by continuing to be apprised by governmental and business legal counsel.

In the United States the EPA provides direct monetary resources, for example, grants and loans, to assess contamination, remediate and train personnel to support brownfield redevelopment. Notwithstanding governmental incentives, however, private lenders are often reluctant to give loans for potentially impaired lands. In some cases, cleanup costs for a property may ultimately be more than the property’s value [19].

Brownfield redevelopment is an exercise in sustainability, both environmental and financial. Any waste management, especially hazardous waste management, requires cleaning up the mess and keeping it clean. Brownfield redevelopment will have additional demands for financial sustainability from groups the waste manager may seldom, if ever, confront. For example, insurance and real estate professionals in the private sector and economic development

committees in the public sector may have very different “bottom lines” or measures of success than those traditionally familiar to the waste manager or environmental engineer. The waste manager should be prepared for a concept-to-completion timeline that is more protracted than a typical cleanup and the private sector may expect longer time horizons and different milestones than what they have experienced in previous real estate development efforts [23]. Environmental assessment and cleanup activities often take longer than many in the private sector or the elected public officials would expect or appreciate.

Communities must address environmental quality as a system. An individual brownfield reuse plan may or may not be optimal when viewed as a comprehensive community-wide context. For example, redeveloping a brownfield should be considered in light of the community’s other land resources, especially the so-called greenfields, those lands that have not been contaminated, but are threatened by urbanization, industrialization, and other land use stress [24]. To make such an evaluation of a reuse plan’s adherence to community goal, requires sound economic and environmental information (e.g., market potential), which may not exist, and if it does, usually does not directly apply to the specific land use decision at hand since it was gathered and collated for other reasons [25]. Closing this knowledge gap can be especially critical for proper redevelopment since a community is defined by more than “off-the-shelf” economic and environmental metrics. Thus success is indicated in part by indicators that are conducive to quantification, for example, change in volume of stormwater runoff, percent of green space, or probability of health risk endpoints, but also financial and economic indicators, for example, net jobs per hectare, internal rate of return, and increase in property value. However, such also depends on more qualitative indicators, such as livability, for example, accessibility and community improvement [26].

8 BEST PRACTICES

A question crucial to any waste management decision is how well does the plan fit with land development practices, codes, design criteria? Land use planning is actually “applied social science.” Proper land development calls for a set of criteria that draws from the ample reservoir of safety criteria, especially these four rules [27]:

1. The design must comply with applicable laws.
2. The design must adhere to “acceptable engineering practice.”
3. Alternative designs must be sought to see better practices are available.
4. Possible misuse of the design must be foreseen.

Land use decisions in the United States are predominantly made at the local level. Durham, NC’s development plan [28] sets the stage for both brownfield redevelopment and greenfield protections. The city considers several land use as a sustainable approach. The city’s unified ordinance, for example, requires that land use decisions consider:

1. Intensity/density of the proposed development, that is, any human-caused change to improved or unimproved real estate that requires a permit or approval from any agency of the City or County of Durham, including but not limited to, constructing or changing buildings or other structures, mining, dredging, filling, grading, paving, excavation or drilling operations, and storage of equipment or materials ;
2. Sensitive areas and related protection;
3. Any limitations on number, type, range of uses, that is, the purpose for which a building, structure, or area of land may be arranged or occupied or the activity conducted or proposed in a building, structure, or on an area of land;

4. Dedications, that is, the transfer without payment of ownership or other interest in real property from a private entity to a public agency or reservations;
5. Design elements if required or otherwise provided; and
6. Development phasing if required or otherwise provided.

Each of these considerations requires that land use decision be based on thorough and scientifically sound information and that the planners, engineers, and others involved in implementing the plan use sound judgment and follow best practices.

9 CONCLUSIONS

As real estate professionals are fond of saying about land, “they aren’t making any more of it.” With the small exception of the Zuiderzee in the Netherlands, the China coastline, the Persian Gulf, and a few other sedimentation projects, this is generally true. So, wasting land by either losing it through erosion, diminishing its beneficial uses and contaminating is wholly unacceptable. Protecting land not only relies on sound application of the physical and natural sciences but also the social sciences. Where people choose to live is based on environmental quality and sociological and psychological factors.

Land use planners, engineers, and waste managers each have vital roles in preventing and addressing land pollution. Waste managers have numerous opportunities to restore and protect land from wastes, including brownfield redevelopment and greenfield protections. They also have opportunities to protect soil and land by ensuring that the operation of waste management facilities do not add environmental stress, such as leakage from landfills and contamination from incinerator plumes.

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Further Reading

- [29] D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Academic Press, 2010.
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Waste Governance

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1 INTRODUCTION

Waste management approaches vary, depending on the jurisdiction. Governance is an inclusive term. The International Risk Governance Council considers risk governance to be at the confluence of numerous analyses and actions related to a technology [1,2], which includes:

- framing the technology in the context of its possible deployment and applications, benefits, and risks for various stakeholders;
- assessing those benefits and risks, including risk perception;
- evaluating other aspects that decision makers will consider before making decisions, for example, specific economic, political, or societal interests;

- identifying options; and,
- communicating potential risk and benefits.

Waste management involves myriad forms of governance, from private individuals who must manage wastes on their own properties, that is, self-governance, to multijurisdictional attempts to prevent the movement of wastes from one part of the globe to another. In the middle is where most waste management governance occurs. The World Bank [3] considers the management of municipal solid waste (MSW) to be the most important role of local governments:

MSW management is the most important service a city provides; in low-income countries as well as many middle-income countries, MSW is the largest single budget item for cities and one of the largest employers. Solid waste is usually the one service that falls completely within the local government's purview. A city that cannot effectively manage its waste is rarely able to manage more complex services such as health, education, or transportation.

Poorly managed waste has an enormous impact on health, local and global environment, and economy; improperly managed waste usually results in down-stream costs higher than what it would have cost to manage the waste properly in the first place. The global nature of MSW includes its contribution to greenhouse gas emissions, e.g. the methane from the organic fraction of the waste stream, and the increasingly global linkages of products, urban practices, and the recycling industry.

All levels of waste governance involve some form of risk reduction, usually addressing a combination of risks to public health, environment, and livability [4]. Risk is addressed extensively in Chapter 35. Certainly the rate of risk reduction is a key metric, but given that waste management is central to all local aspects of local government, there are two key considerations of waste governance, that is, reliability and communication.

No single approach fits for governments providing the most efficient and effective, that is,

reliable services and for ensuring that waste management is inclusive for all stakeholders, and varies with scale. Certainly, local jurisdictions are usually responsible for collection, recycling, composting, and general waste handling. Larger scale jurisdictions, for example, metropolitan waste authorities, seek economies of scale by sharing operations among the local jurisdictions. The highest scale jurisdictions often set standards, for example, limits on the amounts of hazardous wastes, definitions of hazardous and nonhazardous substances, and rules on barrel burning and other less centralized waste disposal approaches.

Most local waste management decisions have low probability of large scale, disastrous outcomes, for example, choice of trucks, daily operations, and landfill protocols. However, like many other environmental engineering decisions, some are low-probability, high consequence events, which present special challenges to local risk managers. When things go wrong, the challenges extend beyond proper failure analysis and risk assessment, but also require clear and factual communications [5]. Two metaphors come to mind when discussing low probability, high impact outcomes, that is, the black swan and the perfect storm. A "black swan" event is one in which the outcome would not have been predicted from past evidence due to the low probability of a possible confluence of events, but the event indeed occurred. A "perfect storm" of a confluence of unlikely events has led to some of the greatest environmental and public health tragedies, such as the combination of factors that led to the disaster from the toxic plume over Bhopal, India [6].

2 GOVERNANCE HIERARCHIES

Although most waste management occurs at the local level, this does not occur in a vacuum. As evidence, during incidents with large-scale impacts, the larger jurisdictions become

increasingly involved. The United States, for example, has three levels of governance with contingency plans for environmental emergencies under the national response system see Fig. 33.1 Area, regional, and federal plans lay out the response, which share planning mechanisms and describe how they interact. Ideally, planning at the release site should be part of an integrated system that involves multiple governmental entities and the public [7].

The risk governance paradigm can start at any level. For example, when a spill or other release of oil or hazardous material occurs in the United States, the source of the release must notify the National Response Center (NRC), which is a component of the National Response System that is staffed 24h a day by the US Coast Guard (see Fig. 33.2). When a report is made, the NRC immediately notifies a designated On-Scene Coordinator (OSC) in the affected region, as well

as tribal, local, and state emergency personnel. The OSC coordinates with the state, other personnel on site, and the Potentially Responsible Party to determine the status of the response. The OSC determines extent of federal involvement and deploys the response actions. The OSC may decide that the response requires outside expertise and resources, for example, contractors, technical support from within EPA or the National Oceanic and Atmospheric Administration. The OSC may also coordinate with one or more of the 13 Regional Response Teams for expertise or to provide additional logistical support [8].

As mentioned, such events are rare, but the waste manager should be aware of the steps to follow when they occur. Even a seemingly small event can be highly disruptive. Often, local governance is called upon for “containment,” that is, limiting the effects of the problem in time

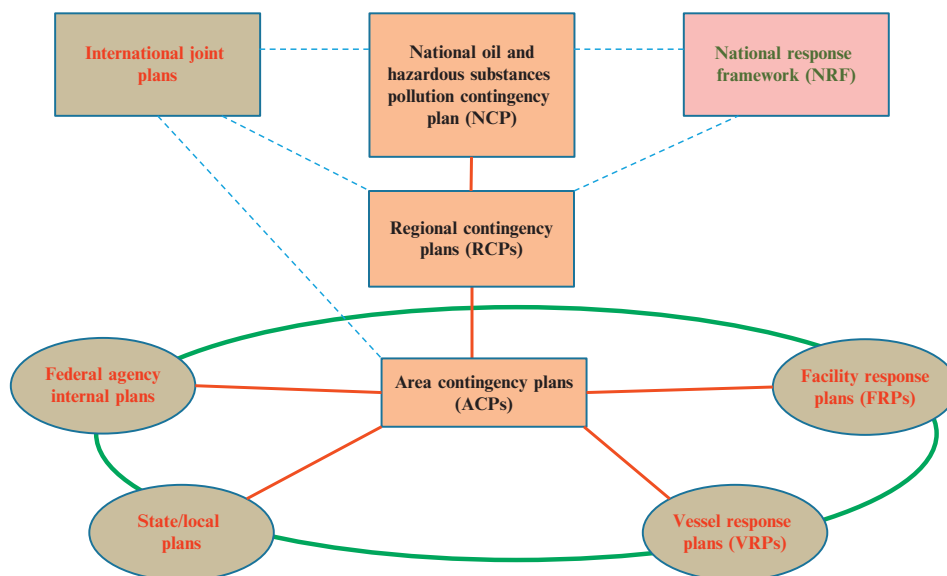


FIG. 33.1 Relationship among the national, regional, and local (area) jurisdictions in the United States, as mandated by the US National Contingency Plan. Dashed lines connect points of coordination, green lines are plans of the within the National Response System (NRS), and red lines are plans within the area contingency plan (ACP). Data from National Academies of Sciences, Engineering, and Medicine, *Spills of Diluted Bitumen From Pipelines: A Comparative Study of Environmental Fate, Effects, and Response*. National Academies Press, 2016; U.S. Environmental Protection Agency, National Response System. 2017. Available from: <https://www.epa.gov/emergency-response/national-response-system>.

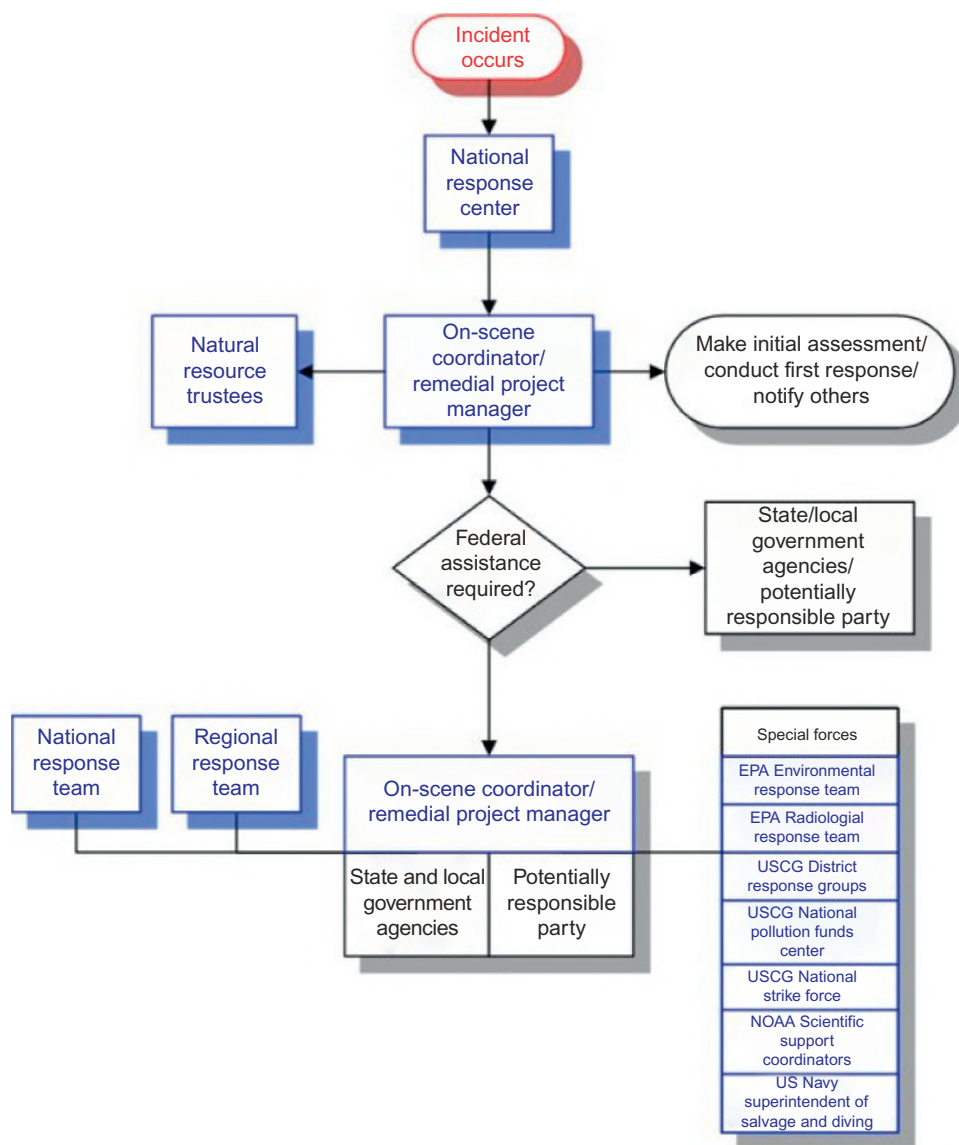


FIG. 33.2 National Response System flowchart. Courtesy: U.S. Environmental Protection Agency, National Response System, 2017. Available from: <https://www.epa.gov/emergency-response/national-response-system>.

and space. Scientific and engineering rigor are essential for rare events, as they are for any risk assessment scenario. Certainly, managing the risks presented by everyday operations or catastrophic failure events rests upon sound decision making and fundamental communication.

Given the diversity of stakeholders in waste management, reaching a consensus on how wastes should be handled is a complex endeavor that depends on a choice of “acceptable” risk [5]. This usually translates into acceptable uncertainty, that is, the amount of uncertainty that

operations will continue as desired. For example, the likelihood that a truck will operate, without breaking down, is never 100%. Purchasing a reliable truck based on historical data helps increase the reliability. So does proper and timely maintenance. However, these actions merely decrease the uncertainty about breakdowns, but do not eliminate it.

3 RELIABLE WASTE MANAGEMENT

The waste manager must ensure that the design, siting, construction, and operation of systems be reliable. The engineer must ensure that any engineered systems have a sufficient optimal operational timeframe, where the failure rate is assumed to be at its lowest. Reliability is the probability that something that is in operation at time 0 (t_0) will still be operating until the designed life (time $t = (t_f)$). As such, it is also a measure of accountability.

Unreliable systems range from occasional and low-impact failures, such as the simple nuisance resulting from fencing is too low to capture windblown litter, to catastrophic, for example, loss of life from an explosion of a combustor. People living near a proposed facility must be ensured the systems will work and will not fail or that in the event of a failure, the harm would be properly managed with an acceptable contingency plan [9]. The probability of a failure per unit time is known as the “hazard” rate. Engineers may recognize it as a “failure density,” or $f(t)$. This is a function of the likelihood that an adverse outcome will occur, but note that it is not a function of the severity of the outcome. The $f(t)$ is not affected by whether the outcome is very severe (such as an explosion where people are hurt or killed) or relatively benign (minor leaf damage from a plume or litter on the road from improper compaction). The likelihood that something will fail at a given

time interval can be found by integrating the hazard rate over a defined time interval:

$$P\{t_1 \leq T_f \leq t_2\} = \int_{t_1}^{t_2} f(t)dt \quad (33.1)$$

where T_f = time of failure.

Thus the reliability function $R(t)$, of a system at time t is the cumulative probability that the system has not failed in the time interval from t_0 to t_f :

$$R(t) = P\{T_f \geq t\} = 1 - \int_0^t f(x)dx \quad (33.2)$$

Reliability can be improved by extending the time (increasing t_f), thereby making the system more resistant to failure. For example, proper engineering design of a landfill barrier can decrease the flow of contaminated water between the contents of the landfill and the surrounding aquifer, for example, a velocity of a few microns per decade. However, the barrier does not completely eliminate failure, that is, $R(t) = 0$; it simply protracts the time before the failure occurs (increases T_f).

Eq. (33.2) illustrates built-in vulnerabilities, such as unscientifically sound facility siting practices or the inclusion of inappropriate design criteria, for example, cheapest land. Such mistakes or malpractice shortens the time before a failure. Thus reliability is also a term of efficiency. Failure to recognize these inefficiencies upfront leads to premature failures (e.g., loss of life, loss of property, law suits, and a public that has been ill served). Risk is really the probability of failure, that is, the probability that our system, process, or equipment will fail. Thus risk and reliability are two sides of the same coin. The common graphical representation of engineering reliability is the “bathtub” curve (see Fig. 33.3). The U-shape indicates that failure will more likely occur at the beginning, so-called infant mortality, and near the end of the life of a system, process, or equipment. Indeed, failure can occur even before acquiring equipment or

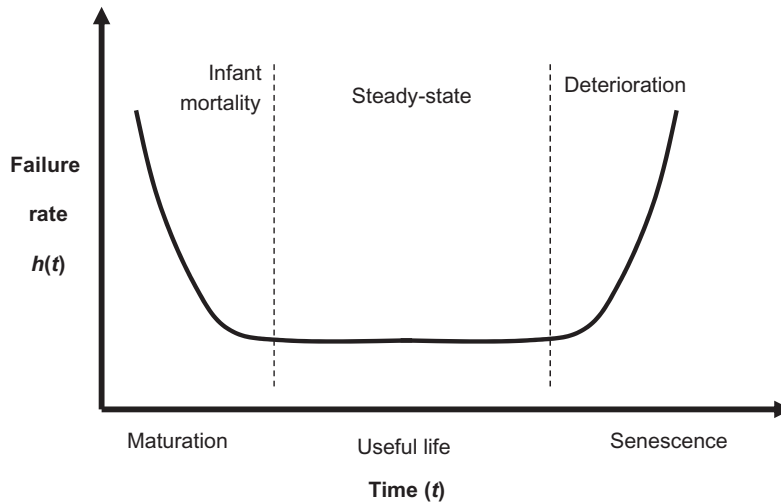


FIG. 33.3 Prototypical reliability curve. The highest rates of failure, $h(t)$, occur during the earliest and latest stages. Well-designed systems extend the useful life. The waste manager and engineer must build in factors of safety, including closer monitoring of more extensive safeguards when the failure rates are likely higher at the beginning and toward the end of the steady-state period. Reproduced with permission from D. Vallero, *Paradigms Lost: Learning From Environmental Mistakes, Mishaps and Misdeeds*. Butterworth-Heinemann, Burlington, MA, 2005.

starting a new route. In fact, many problems occur during the planning and idea stage. A great idea may be dismissed prematurely.

4 SUCCESS IN WASTE MANAGEMENT

Waste management is bounded by numerous policies, laws, and other societal norms. As discussed in [Chapter 35](#), risk is an expression of operational success or failure. Management is the means of navigating among the policies, laws, and competing interests to achieve goals. Science and engineering are essential to good waste management, but not sufficient. Waste management must draw on other knowledge. The waste manager must apply reasoning of all types, deductive, inductive and, yes, intuitive. Certainly, wastes cannot be completely managed by intuition-based decisions, but intuition is not always wrong [10]. It is important to keep in mind that many of the stakeholders in a

jurisdiction apply intuitive reasoning often and, for some, almost exclusively. Intuition, in the author's opinion, is often fact based, deductive or inductive reasoning that has long been forgotten. For example, most professions require a substantial amount of time spent working under a senior professional before one is granted a license. The senior professional may have long forgotten the specifics of why and how something works, but has logged the process in memory. Indeed, the newly minted professional may know exactly why and how, but has only applied this limited knowledge within the highly controlled academic or laboratory setting, whereas the seasoned professional has been applying these principles in the real world.

Having all the data needed for a *completely* informed waste management decision is impossible. Scientific objectivity and humility dictate that decision makers are upfront about uncertainties. Sometimes, waste questions can only be answered by looking for patterns and analogies from events that are similar to the potential

threat being considered. From there, scenarios can be developed to follow various paths to good, bad, and indifferent outcomes. This is known as a decision tree. This is not the same, necessarily, as the one with the most benefits compared to risks, that is, a benefit to risk ratio or relationship, or benefit to cost ratio or relationship. However, this is indeed one of the more widely used approaches. The challenge is how to quantify many of the benefits and risks.

Humility is always the watchword for waste management. Usually, there is more than one cause of a problem and more than one solution to the problem. Caution is in order when attributing a cause. The association of two factors, such as the level of exposure to a compound and the occurrence of a disease, does not necessarily mean that one necessarily “causes” the other. Often, after study, a third variable explains the relationship. However, waste manager must be diligent in linking causes with effects. Otherwise, corrective and preventive actions cannot be identified. So, strength of association is a beginning step toward cause and effect. A major consideration in strength of association is the application of sound technical judgment of the weight of evidence.

5 CAUSAL LINKS

Assigning causality when none really exists must be avoided but, if all we can say is that the variables are associated, the public is going to want to know more about what may be contributing an adverse effect (e.g., learning disabilities and blood lead levels). This was particularly problematic in early cancer research. Possible causes of cancer were being explored and major research efforts were being directed at myriad physical, chemical, and biological agents. So, there needed to be some manner of sorting through findings to see what might be causal and what is more likely to be spurious

results. Sir Austin Bradford Hill is credited with articulating key criteria that need to be satisfied to attribute cause and effect in medical research [11].

5.1 Strength of Association

Strong associations provide more certain evidence of causality than is provided by weak associations. A cause must be associated with an outcome, that is, the statistical association cannot be zero, although a cause may show up as a very low statistical association. Common metrics used to indicate association include risk ratio, odds ratio, and standardized mortality ratio.

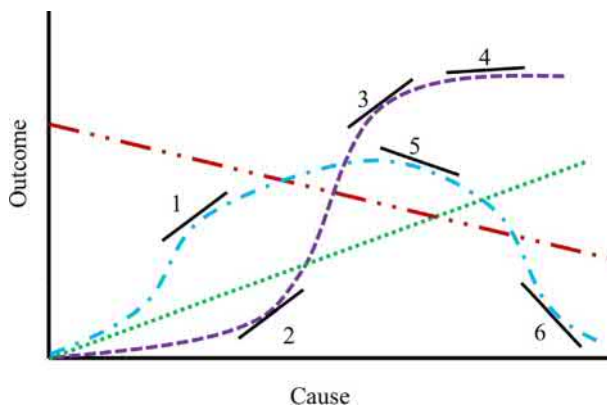
5.2 Consistency

If a cause is associated with an outcome consistently under different studies using diverse methods of study of assorted populations under varying circumstances by different investigators, the link to causality is stronger. For example, if results are similar for waste collection approaches studied with scenarios, simulated with models, and documented using historical information, there is greater consistency. However, if there is no agreement with the various approaches, this could mean that the results are unique to a given set of conditions, for example, if the only scenarios were towns with populations less than 5000, a model was parameterized only for one type of collection approach, or historical data are incomplete or erroneous.

5.3 Specificity

The specificity criterion holds that the cause should lead to only one outcome and that the outcome must result from only this single cause. Recall that Hill was interested in cancer and was viewing causality through a biomedical

FIG. 33.4 Hypothetical cause-outcome curves. The green and purple lines have positive slopes. The red line has a negative slope. The blue line starts as a positive slope but becomes negative. The slope varies on the curves, that is, the purple and blue lines, so must be measured instantaneously at a tangent to the curve (1–6). Slopes 1, 2, 3, and 4 are positive. Slopes 5 and 6 are negative. The linear cause-outcomes are common expressions of scientific principles, for example, gravitation, but not in most engineering and waste management situations.



perspective, that is, this criterion appears to be based in the germ theory of microbiology, where a specific strain of bacteria and viruses elicits a specific disease. This is rarely the case for waste management.

5.4 Temporality

This criterion requires that exposure to the chemical must precede the effect. For example, in a retrospective study, the researcher must be certain that the outcome was not already present before the contributing factors were present. For example, a disease may have been present before a toxic release. However, this does not always eliminate the temporal link, for example, a disease like asthma may be present before a toxic emission, but the incidence may increase and/or the symptoms and disease progression are exacerbated. Thus it may not mean that the agent in the release is not a cause, but it does mean that it is not the sole cause of the disease (see “Specificity”), or that the outcome is not new, so much as a worsening of an existing condition.

5.5 Gradient

If the force of a cause, for example, the intensity and extent, increases the amount of outcome, this strengthens the causal link. This is a

common metric for risk assessment, known as the “dose-response” step in risk assessment (see Chapter 35). If the level, intensity, duration, or total level of chemical exposure is increased a concomitant, progressive increase should occur in the toxic effect. However, the gradient also applies to other areas, for example, if a recycling program is intensified and the amount of recycling increases concomitantly, this is a gradient.

In waste management the gradient is seldom linear. Thus depending on the shape of the curve, it must be measured at a finite time value, that is, a tangent to the cause-outcome curve (see Fig. 33.4).

5.6 Scientific Plausibility

Hill limited this to biological plausibility, but the criterion has wider application. Generally, an association needs to follow a well-defined explanation based on a known scientific system, that is, a paradigm. A paradigm, however, is mutable. Even some of the most strongly held scientific laws have had to be revised with the evolution of knowledge [12]. Outside of research, this caution has little relevance to the practice of waste management. Engineers and other professionals involved in managing wastes must apply best practices according to

their profession. If results are implausible according to underlying scientific principles, they should be heeded. However, this applies to scientific and engineering principles, and not one's one "favorite" practice. Simply because an approach does not follow direct from what has worked in the past, does not render it implausible, but merely inconvenient. Indeed, the waste manager must beware of Kaplan's "law of the instrument." The waste manager's or engineer's preferred approach can be likened to a hammer, so that the entirety of waste management is a collection of nails. There are likely to be other plausible "tools," besides one's hammer and there are certainly myriad other problems besides the "nails." This can be particularly worrisome for modelers, who often must incorporate simplifying assumptions to make the math work. Engineering models, for example, can be accused of assuming that a chicken is spherical, but when the designed coop fails, this may be in part due to this oversimplification. After all, the real-world coop's chickens have beaks, feathers, and claws.

5.7 Coherence

The criterion of coherence suggests that all available evidence should form a cohesive whole. By that, the proposed causal relationship should not conflict or contradict information from experimental, laboratory, epidemiologic, theory, or other knowledge sources.

5.8 Experimentation

Experimental evidence useful to waste management can support a causal hypothesis. Laboratory experiments, tests, pilot studies, physical models, and natural experiments (e.g., a disaster response) are available. The experiment does not have to be specific, but can be drawn from

others' experiences, for example, an informatic experiment using "big data."

5.9 Analogy

The term analogy implies a similarity in some respects among things that are otherwise different. It is thus considered one of the weaker forms of evidence.

For waste management decisions, some of Hill's criteria are more important than others. Reliability in a public health and environmental context relies heavily on strength of association, for example, to establish dose-response relationships. Coherence is also very important. Animal and human data should not be extensions of one another and should not disagree. Biological gradient is crucial, since this is the basis for dose-response (the more dose, the greater the biological response).

Temporality is crucial to all scientific research, that is, the cause must precede the effect. However, this is sometimes difficult to see in some instances, such as when the exposures to suspected agents have been continuous for decades and the health data are only recently available.

Linking causes to outcome must be based on sound science and scientific judgment. Waste managers must consider whether the selected approach will likely continue to "work" (reliability) and, further, must consider the hazards that may arise, especially in a new and untested technology is selected. Risk is a function of likelihood that the hazard will in fact encounter, so the waste manager is also tasked with predicting the adverse implications that society might face. Thus the "risk" associated with a selected approach refers to the possibility and likelihood of undesirable and possibly harmful effects. Errors in reliability and risk predictions can range from not foreseeing outcomes that are merely annoying (e.g., fuel efficiencies that are less than expected) to those are devastating (e.g., the release of carcinogens from an incinerator or landfill leachate) [13].

6 WASTE EPIDEMIOLOGY [14]

The causal link begins with the “weight of evidence” (WoE). The scientific literature varies in its use of WoE. It can be [15]:

1. metaphorical, where WoE refers to a collection of studies or to an unspecified methodological approach;
2. methodological, where WoE points to established interpretative methodologies (e.g., systematic narrative review, metaanalysis, causal criteria, and/or quality criteria for toxicological studies) or where WoE means that “all” rather than some subset of the evidence is examined, or rarely, where WoE points to methods using quantitative weights for evidence; and,
3. theoretical, where WoE serves as a label for a conceptual framework.

Epidemiology can be either descriptive or analytical. Often, descriptive epidemiology is the first step in identifying a public health problem. Descriptive datasets (e.g., census data, remote sensing data, state health summaries, etc.) provide the first clues from which scientists may generate hypotheses as to what may be causing or contributing to a health problem. These data may allow epidemiologists to characterize differences in demographic and disease outcomes. Sex, race, ethnicity, age, and socioeconomic factors can show different outcomes for diseases in the same general population.

Several statistical tools can aid in the transition from descriptive to analytical epidemiology. Relative risk (RR) is indeed an expression of strength of association and often used to help represent WoE. Relative risks can be visualized

as a two-by-two table, that is, $RR = \frac{\left(\frac{A}{A+B}\right)}{\left(\frac{C}{C+D}\right)}$.

The difference in age, sex, and whether one lives in a rural versus urban area can be among the first descriptive comparisons conducted by

epidemiologists, as in a recent study of mortality rates for diseases in the Hubei Province in China (see [Table 33.1](#)).

The table shows the differences between crude and standardized death. The standardization is accomplished by adjusting the crude death rate for differences in age composition between the study group (urban and rural) versus that of the standard population. This allows for comparisons of asymmetrical distributions within subpopulations, so that risk factor being investigated is less influenced by factors (i.e., confounders).

Standardization can be accomplished directly or indirectly. For example, standardizing for age can be done using the direct standardization method, which calculates a weighted average of the study group’s age-specific mortality rates where the weights represent the age-specific sizes of the standard population. Each age-specific mortality rate is multiplied by the number of people in the age group of the standard population. These product values are summed and then divided by the number of people in the standard population. An example of standardization used by US Center for Disease Control and Prevention is presented in [Table 33.2](#).

The indirect method applies age-specific mortality rates from the standard population to derive expected deaths in the region’s population. For each age group, the age-specific mortality rate for the standard population is multiplied by the number of people in age group of the study group and summed. This number of deaths in the entire study group is divided by this sum. The result is multiplied by the crude death rate.

Note that the last column in [Table 33.2](#), relative risk, includes confidence intervals. This is an indication of the uncertainty in the estimates. The odds ratio is the probability that an event will occur divided by the probability that it will not occur. It can also reflect the odds of an event for one group (e.g., urban dwellers) divided by the odds of a different group (e.g., rural population). Rather than presence or absence, the information in [Table 33.2](#) can be compared for urban and rural populations (see [Table 33.3](#)). Here, the

TABLE 33.1 Mortality Rates of Chronic Disease Among Men in Urban and Rural Areas in Hubei Province, China; 2008–10.

Diseases	Urban		Rural		Standardized Relative Risk (95% confidence interval)
	Crude Death Rate (per 100,000)	Standardized Death Rate (per 100,000)	Crude Death Rate (per 100,000)	Standardized Death Rate (per 100,000)	
Circulatory system	351.34	301.63	400.99	582.55	1.93(1.88–1.98)
Cerebrovascular disease	193.86	165.27	260.32	369.75	2.24(2.16–2.31)
Ischemic heart disease	118.33	102.80	86.81	128.44	1.25(1.19–1.31)
Neoplasms	257.23	220.77	240.01	286.61	1.30(1.26–1.34)
Lung	110.94	94.61	46.95	74.31	0.79(0.75–0.83)
Liver	39.26	34.34	49.02	53.44	1.56(1.44–1.68)
Stomach	26.98	22.81	45.16	56.22	2.47(2.25–2.70)
Colon and rectum	19.92	16.93	8.04	9.85	0.58(0.51–0.66)
Esophagus	22.54	19.69	13.80	23.00	1.17(1.05–1.30)
Breast	0.43	0.36	0.25	0.32	0.85(0.38–1.87)
Respiratory system	82.28	70.15	134.23	215.28	3.07(2.92–3.23)
Chronic lower respiratory disease	61.49	52.09	130.52	210.83	4.05(3.82–4.29)
Digestive system	26.76	23.25	21.03	24.62	1.06(0.96–1.17)
Diseases of liver	12.83	11.25	11.29	12.08	1.07(0.93–1.24)
Endocrine, nutritional, and metabolic diseases (E00–E90)	25.55	21.87	10.05	13.31	0.61(0.54–0.68)
Diabetes mellitus	24.44	20.91	9.64	12.80	0.61(0.55–0.69)

Data from L. Cheng, et al., *Chronic disease mortality in rural and urban residents in Hubei Province, China, 2008–2010*, *BMC Public Health*, 13 (1) (2013) 713.

risk factor is a differentiation as to where people live. For some outcomes “urbanization” appears to be protective for several of the diseases listed in Table 33.1. The rural population had higher relative risks for cerebrovascular diseases, ischemic heart disease, stomach cancer, and liver cancer; whereas the urban populations exhibited high relative risks for lung, colorectal and breast cancer, endocrine diseases, and diabetes. Since some, but certainly not all, of these diseases share some risk factors, this descriptive

epidemiology indicates the need to investigate what it is about urban and rural life that leads to these differences.

Descriptive information like that in Table 33.1 is an early step in generating hypotheses and provoking ideas about WoE and, ultimately, causality. This is a type of analytical epidemiology, that is, possible explanations of why there are differences among the different segments. Since air pollution risk is a function of the pollutant’s inherent hazard (e.g., cancer potency) and the

TABLE 33.2 Example of Age-Adjusted Standardization of Mortality Rates

Crude Death Rate Comparison						
Age	Community A			Community B		
	Deaths	Population	Rate (per 1000)	Deaths	Population	Rate (per 1000)
0–34 years	20	1000	20	180	6000	30
35–64 years	120	3000	40	150	3000	50
65 years and over	360	6000	60	70	1000	70
Total	500	10,000	50	400	10,000	40

Age-Adjusted Death Rate Calculation					
Age	Community A			Community B	
	Standard population	Rate (per 1000)	Rate × population	Rate (per 1000)	Rate × population
0–34 years	3000	20	60	30	90
35–64 years	3000	40	120	50	150
65 years and over	4000	60	240	70	280
Total	10,000	42	420	52	520

Data from L.R. Curtin, R.J. Klein, *Direct standardization (age-adjusted death rates)* (no. 6). US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Center for Health Statistics, 1995.

TABLE 33.3 A 2 × 2 Table Representing Two Risk Factors (Living in an Urban Area or Rural Area) and Two Outcomes (Disease or No Disease), From Which Relative Risk Can be Calculated.

Risk Factor	Outcome: Disease	Outcome: No Disease	Total
Urban	A	B	A + B
Rural	C	D	C + D

Reproduced with permission from D. Vallero, *Translating Diverse Environmental Data into Reliable Information: How to Coordinate Evidence from Different Sources*. Academic Press, London, UK, 2017.

exposures (e.g., inhaling air containing the pollutant), outcomes like those in the far-left column of Table 33.1 are often low outcomes, such as the number of cancers added to what would otherwise be expected without the pollution. This calls for statistics to express the linkages between the hazards and exposures, often beginning with the odds ratio for these events.

The odds ratio is the first step toward linking a risk factor to the adverse outcome, since it reflects the strength of the association between an exposure and an outcome, that is, the odds that an

outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure [16]. For example, the Children's Health Study in southern California used odds ratios to link indicators of respiratory problems in children with proximity to major roadways (mobile air pollutant exposure). Asthma medication usage (odds ratio=1.50; 95% confidence interval, 1.16–1.95), wheezing (odds ratio=1.40; 95% confidence interval, 1.09–1.78), and lifetime asthma incidence (odds ratio=1.29; 95% confidence interval, 1.01–1.86)

for children residing in homes within 75m of a major road [17]. The odds ratios of 1.50, 1.40, and 1.29 indicate that living near a roadway is associated with 50% more children used medication, 40% more children exhibited wheezing, and 29% more children were diagnosed for asthma compared to those living in homes greater than 75m from a major roadway.

Note also that each odds ratio is expressed within a confidence interval. This is a way of expressing uncertainty and variability. This means that 95% of the time for children living within 75m from a major road, the odds ratio for asthma medication usage ranged from 1.16 to 1.95. If the lower interval were less than 1, this is taken to mean that the exposed and unexposed were not statistically different, that is, living near or far from a roadway makes no statistical difference for a variable with a confidence lower interval less than 1. However, in this case, the low value of 1.16 is greater than 1, indicating that there is a statistical difference. It is up to the scientist to determine why.

Risk is stated as a probability, that is, the likelihood of an outcome; specifically, an adverse or unwanted outcome. Probability is the mathematical expression that relates an outcome of an event to the total number of possible outcomes. For example, since coin has only two sides, flipping it should give 50–50 chance of either heads or tails. However, the 50% probability depends on every physical factor on each side being equal. Indeed, this is not the case for most coins, since the heads side usually has a head and the tail side has something other than a head. Thus the aerodynamics differs due to shape, ridges, and valleys on the two sides. These are deterministic features that may make the odds change ever so slightly.

7 WASTE COMMUNICATIONS: AVOIDING THE TECHNO- POLYSEMY PROBLEM

Waste management information must be presented in a meaningful way without violating overextending the interpretation of the data.

Waste managers must clearly present scientifically sound information. Presentation is not an end in itself, but a means toward the end of obtaining feedback and approval. This goal requires input and understanding of the options and decision-making process by decision makers of diverse backgrounds and perspectives. Arguably more important, the options and processes must be sufficiently clear to a wider group of stakeholders, especially of those most directly or indirectly affected by the ultimate decisions. This may seem to be an untenable task but the waste manager must be able to communicate effectively to ensure the optimal choices are made regarding designs, to ensure that these technically sound designs are accepted by all appropriate levels of governance and stakeholders, and to convey sufficient information to the waste management personnel so that the designs are operated and maintained satisfactorily.

Technical communication can be seen as a critical path, where the engineer sends a message and the audience receives it (see Fig. 33.5). The means of communication can be either perceptual or interpretative [18]. Perceptual communications are directed toward the senses. Human perceptual communications are similar to that of other animals; that is, we react to sensory information (e.g., reading body language or assigning meaning to gestures, such as a hand held up with palms out, meaning “stop” or smile conveying approval).

Governance must address emerging technologies, including those related to waste management, for example, nanotechnology, biotechnology, and genetic engineering to treat wastes. This calls for collaborative approach to consider the views of multiple pertinent stakeholders [19]. Indeed, the waste manager may spend most of the workday with fellow technologists. However, this is but a small group of the full set of stakeholders. Whereas the communication methods toward the right-hand side of Fig. 33.5 may be appropriate for the fellow technologists, this may be unclear to others. As presented in Table 33.4, technologists tend

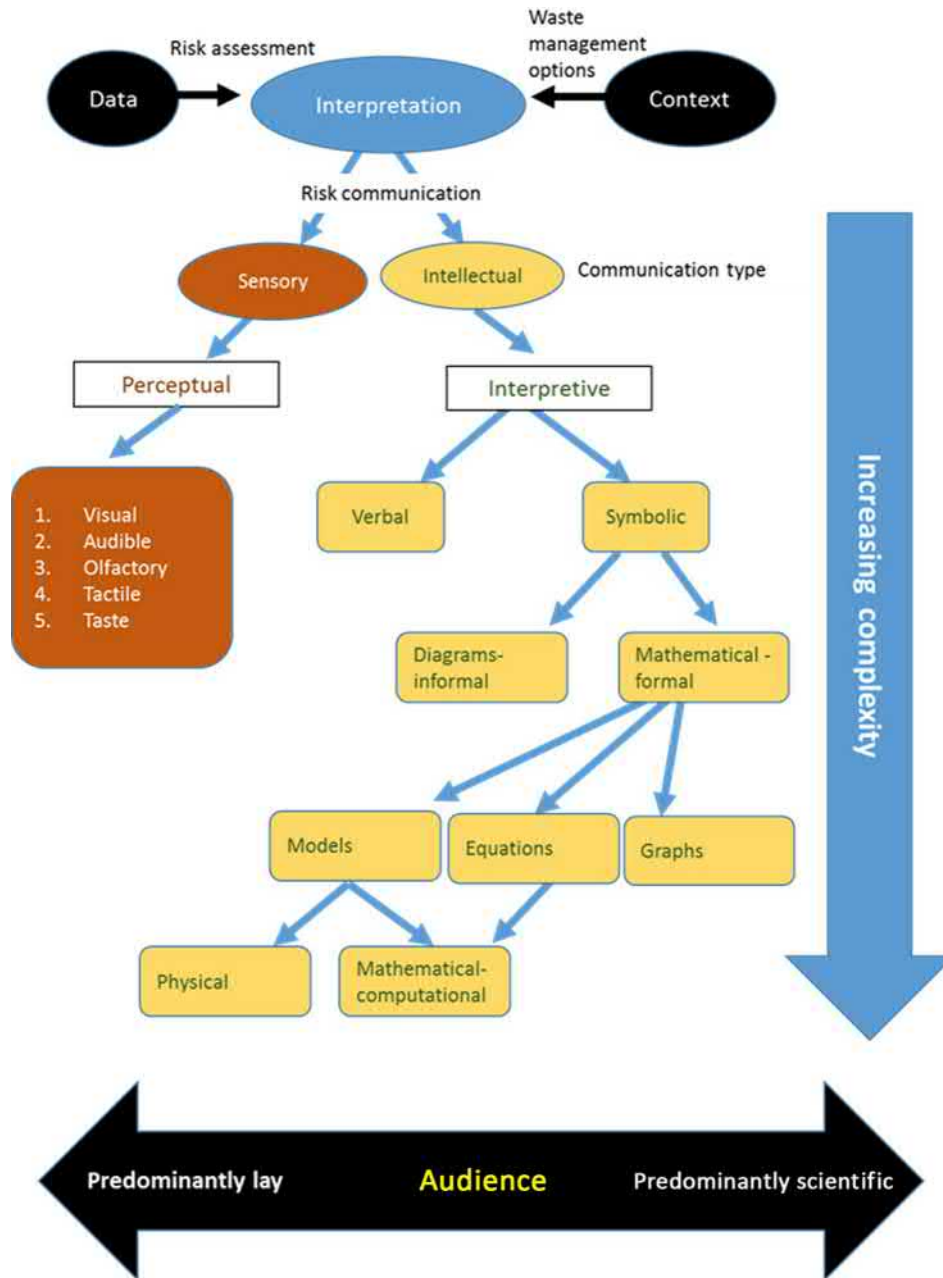


FIG. 33.5 Waste-related communication techniques. All humans use perceptual communication, such as observing body language of an engineer or smelling an animal feeding operation. The right side of the figure is the domain of technical communication. Thus the public may be overwhelmed by perceptive cues or may not understand the symbolic, interpretive language being used by a bioengineer and others in the risk communication process. Thus the type of communication in a scientific briefing is quite different from that of a public meeting or a briefing for a neighborhood group potentially affected by a risk management decision. Data from M. Myers, A. Kaposi, *A First Systems Book: Technology and Management*. Imperial College Press, 2004; T.R. Green, *Cognitive dimensions of notations*, in: *People and Computers V*, 1989, pp. 443-460.

TABLE 33.4 Two Methods of Processing Information: Science-Based Risk Assessment and Risk Perception.

Type of Analysis	Risk Assessment Methods	Risk Perception Processes
Identification of risk	Technical monitoring and measurement of event - Physical - Chemical - Biological	Awareness Unique personal processes
Risk estimation	Deductive reasoning From general principles to specific event	Intuition
	Statistical inference	Historical reference, e.g., similar events
		Reliance of authority and media coverage
Risk evaluation	Benefit-to-cost ratios Risk-to-benefit calculations Alternative selection Economic and feasibility studies Policy analysis	Advice for trusted others
		Personality factors
		Individual actions
		Personal or business profit

Redrawn from K. Smith, *Environmental Hazards: Assessing Risk and Reducing Disaster*. London, UK, Routledge, 1992.

to be comfortable with scientifically based risk information in the green column; many stakeholders prefer to communicate using on perception processes in the blue column.

Interpretive communications encode messages that require intellectual effort by the receiver to understand the sender's meanings. This type of communication can either be verbal or symbolic. Scientists and engineers draw heavily on symbolic information when communicating among themselves. If you have ever mistakenly walked into the seminar or meeting in which experts are discussing an area of science not memorable to you, using unrecognizable symbols and vernacular, this is an example of symbolic miscommunication.

The challenge is to say what needs to be said *and* to have the audience hear and see what needs to be understood. Using plain language is not enough if it fails to capture the important aspects that underlie the decision at hand. In fact, compared to everyday language and creative writing, where ambiguity may even be intended, the meaning of technical and scientific terms is usually distinct and univocal, at least within a particular discipline.

Another problem arises when one is convinced of understanding what is being discussed, but is interpreting it inaccurately through one's predetermined filters. Let us coin this as the "techno-polysemy problem." Homonyms are terms with more than one meaning. Polysemes are words that also have one meaning, but at least two of the meanings overlap.

Let us assume that in the meeting you crashed, the experts are using words and symbols that are used in your area of expertise, but with very different meanings. For example, psychologists speak of "conditioning" [20] with a very different meaning than that of an engineer [21], which is different from that of a statistician or mathematician [22, 23], and altogether different from that of sludge or compost handler [24, 25]. Perhaps, most people in a waste-related public meeting or hearing, or even a meeting with decision makers in a jurisdiction, have *no* concept of the term, except when applied to air conditioning or a swimming pool. The waste manager may have all of these in the audience and must be certain that both clearly understand such homonyms. The waste manager is reminded that a word or phrase *will mean* what it *can mean* [26].

8 EMERGING TOOLS AND TECHNIQUES

Addressing wastes requires data of various sources. The data may be qualitative, semiquantitative, and quantitative information, which are evaluated according to widely varying criteria of risk, cost, benefit, social implications, and other considerations from which governance decisions are made [19]. Today, much is written about “big data,” that is, widely available and searchable datasets. The waste manager must be cautioned that applying such secondary data sources to predict extremely low probability events is almost invariably to some extent wrong. After all, the data were not collected with a later user’s purposes in mind. However, they do have value. Certainly, a complete replication of the events that led to the data is not possible, but recurrent precedents that seem to occur repeatedly prior to environmental disasters should be heeded. The past can indeed be an indicator of the future, notwithstanding their inherent imprecision and inaccuracy of using other people’s data. So, both the stockbroker’s and Santayana’s seemingly incongruent admonitions, which respectively are:

Past performance is not an indicator of future results.

Those who cannot remember the past are condemned to repeat it [27].

8.1 Cluster Analysis

Secondary data may be analyzed with statistics and probability, including cluster analysis. To be useful to the waste manager, observations and events (known as “objects” to the data miner) must be grouped according to affinities and information found in the data describing the objects or their relationships. This allows the objects comparisons based on similarities and relationships between and among object groups. When objects within a group have greater similarity (i.e., homogeneity), then they

can be distinguished by this greater difference between groups, which allows for improved clustering. Usually, cluster analysis aids in reaching a finding by concisely and clearly classifying the data into distinct, nonoverlapping groups.

If the distinctions are not short, this is “fuzzy clustering,” that is, an object is a partial member of two or more groups [14]. An example in Fig. 33.6 shows an applied hierarchical clustering analysis (HCA) to develop harmonized functions (HF) of consumer products [28]. The HCA identified 269 HF clusters, that is, clusters of similar reported functions. These clusters capture a much of the variance in pairwise distance between chemicals. This technique can be complemented with text analytics, for example, when an HF captured multiple reported functions. This indicates that chemical ingredients in that product use category may serve multiple functional uses, such as when the “surfactant” HF has such commonly occurring reported functions as “surfactant,” “cleaner,” “hydrotrope,” and “emulsifier.” Thus techniques like cluster analysis and text analytics are very useful as databases on product ingredients are becoming more widely available [29–31].

There are numerous approaches to grouping mined data according to the needs of the waste manager, for example, based on grouping physicochemical properties of waste, types of products being used, likelihood of contact with waste constituents. These techniques can be combined, such as using both cluster analysis or principal components analysis to categorize solvents [32–34].

8.2 Spatial Analysis

Spatial tools are also available to improve the reliability of estimates in areas that are difficult to find a signal against the background noise, for example, risk factors in sparsely populated geographical entities. Most waste managers are familiar with geographic information systems (GIS). These systems are now commonly used for optimizing collection routing, landfill and incinerator siting, first and emergency response,

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Harmonized function

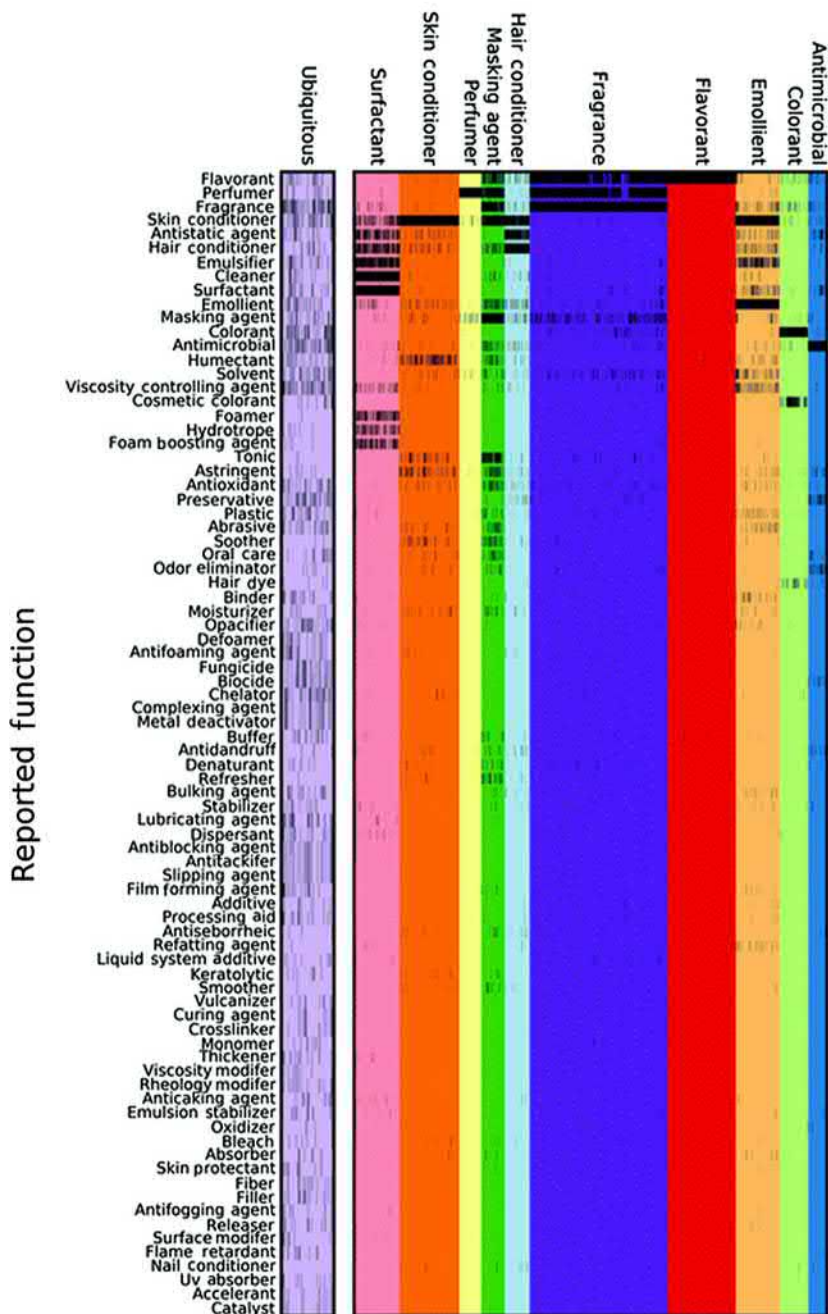


FIG. 33.6 Cluster analysis of reported functions compared to harmonized functions of consumer product categories. The function “fingerprints” of chemicals in the 10 largest HF clusters and the ubiquitous, harmonized function cluster in terms of the most frequently occurring original reported functions. Reported functions are on the horizontal axis; harmonized functions are on the vertical axis. *Reproduced from K.A. Phillips, J.F. Wambaugh, C.M. Grulke, K.L. Dionisio, K.K. Isaacs, High-throughput screening of chemicals as functional substitutes using structure-based classification models, Green Chem. 9 (2017) 1063–1074.*

and public information [35]. New techniques now available to augment GIS, for example, smoothing, are aiding in the identification and delineating of clusters of interest, such as elevated cancer risk that would be missed if spatial outliers can be detected and not filtered out. Static mapping techniques poorly predict the spatial distribution of risk and its associated variance, thus uncertainties are not properly accounted for and propagation of local cluster

analysis is not possible (see Fig. 33.7) For example, the smooth risk maps of rare outcomes (e.g., cancer clusters around a landfill) generated by a Poisson kriging geostatistical simulation provides superior estimates of risk than does the typical model that graphs a semivariance, that is, the spatial dependence between two observations as a function of the distance between them, that is, the semivariogram modeling method [36].

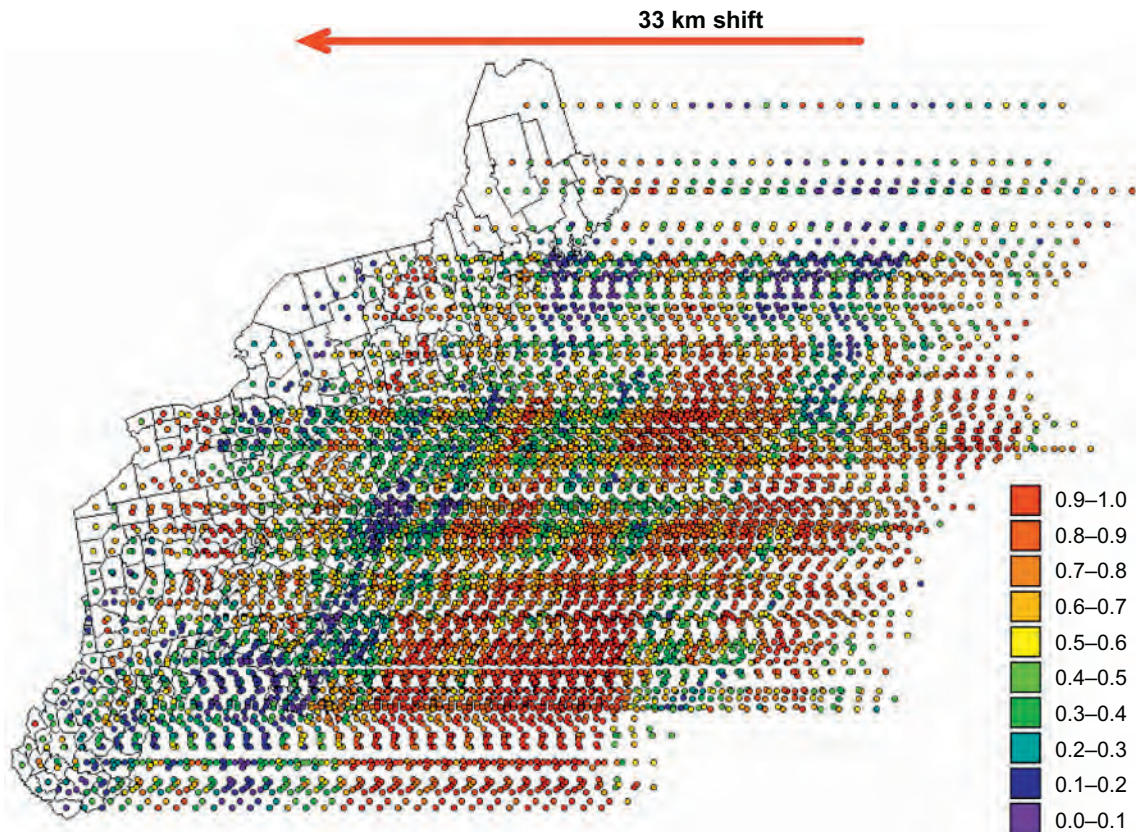


FIG. 33.7 Animated displays of simulated maps generated by Goovaerts using the p-field method. Simulation grid is first generated by shifting the 295 county centroids by east-west increments of 33km. Probability values populate the grid using sequential Gaussian simulation and the risk semivariogram models. The derived probability values are then used to sample Gaussian local distributions of probability characterized by the Poisson kriging estimate and variance mapped using Monte Carlo simulation. *Reproduced from P. Goovaerts, Geostatistical analysis of disease data: visualization and propagation of spatial uncertainty in cancer mortality risk using Poisson kriging and p-field simulation, Int. J. Health Geogr. 5 (1) (2006) 7; Note: SpringerOpen is the original publisher of this figure, which allows it to be reprinted here (<https://www.springeropen.com/about/reprints-and-perm>).*

These simulations are constructed in a step-wise fashion [36]:

1. From observed mortality rates and population of interest data, Poisson kriging is applied to model local risk uncertainty within each geographical unit.
2. Next, spatially correlated probability values generated using nonconditional sequential Gaussian simulation samples the set of local probability distributions.

3. By slowly sampling moving probability fields, incrementally different realizations are created, which can serve as consecutive animation frames, yielding a dynamic display of the uncertainty that evolves and appends to the risk spatial distribution.

The supplementary material in Goovaerts [36] provides the software and input data files to generate these simulations, maps, and visualizations for breast and cancer mortality rates in sparsely populated regions (see Fig. 33.8).

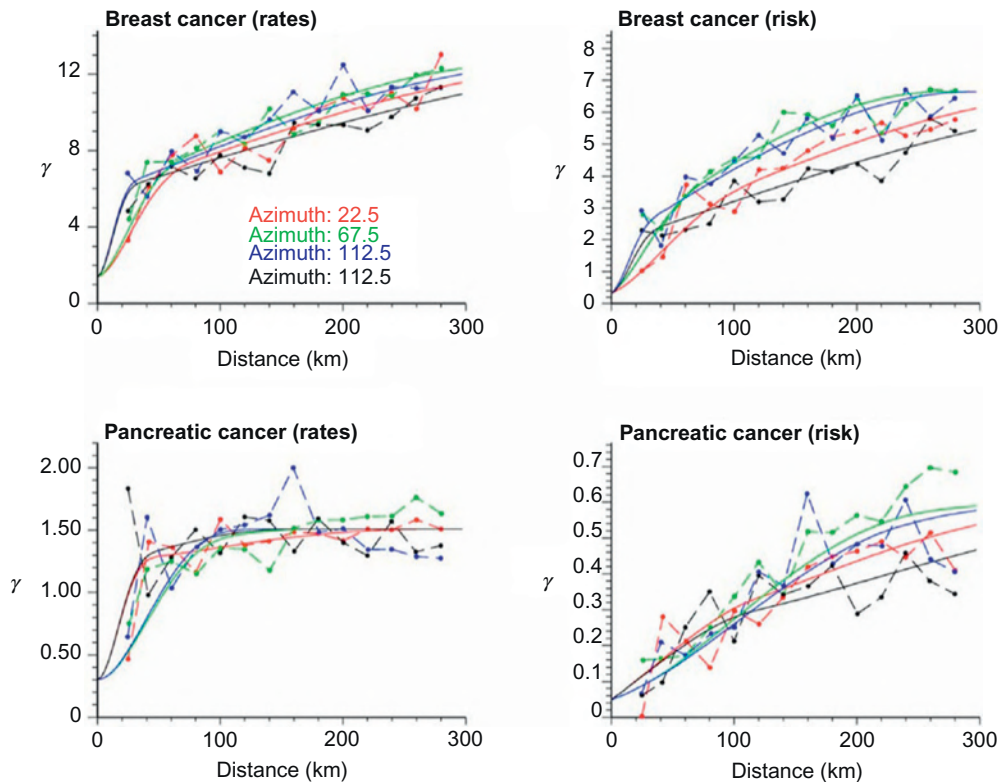


FIG. 33.8 Directional semivariograms generated by Goovaerts showing breast and pancreatic cancer mortality rates and risks in sparsely populated regions in the northeastern United States. The semivariograms of raw mortality rates (left column) and the semivariograms of the risk are computed in four directions (shown in top left graph); azimuth angles are measured in degrees clockwise from the N-S axis. The solid curve denotes the anisotropic (i.e., direction-dependent) model fitted using weighted least-square regression. Reproduced with permission from P. Goovaerts, *Geostatistical analysis of disease data: visualization and propagation of spatial uncertainty in cancer mortality risk using Poisson kriging and p-field simulation*, *Int. J. Health Geogr.* 5 (1) (2006) 7; software: *poisson_kriging.exe* P. Goovaerts, *Geostatistical analysis of disease data: estimation of cancer mortality risk from empirical frequencies using Poisson kriging*, *Int. J. Health Geogr.*, 4 (1) (2005) 31. Note: SpringerOpen is the original publisher of this figure, which allows it to be reprinted here (<https://www.springeropen.com/about/reprints-and-perm>).

9 CONCLUSIONS

Every level of governance specifies measures of success for waste management. All aspects of waste management success depend on reliability. Decisions regarding the most suitable options, developing plans, implementing actions, and reviewing success must use reliability as a gauge of performance. A reliable program must also draw from scientific and other data and decision tools, as well as the expertise and perspectives of wide range of stakeholders and governance. This necessitates effective communications, which must be tailored to the needs, interests, and understanding of this eclectic audience.

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Waste Constituent Pathways

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OUTLINE

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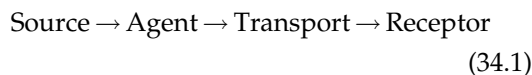
1 INTRODUCTION

Almost every human activity in a jurisdiction produces waste. However, the pathway from the activity to harm varies widely. An emerging problem is the amount of parent and residue constituents from the residential use of pharmaceuticals and personal care products. In addition to the traditional concern of such toxic substances from industry, recent studies have shown elevated concentrations of these substances in water resulting from landfill leachate, down the drain, and improper disposal [1–3]. Upon its arrival at a landfill or other disposal site, a waste that contains these substances undergoes transformations and processes such as desorption, in which a pathway begins that could reach vulnerable receptors [3–8].

Wastes contain biological, chemical, and physical substances that can stress human

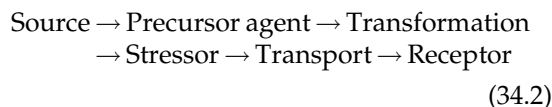
health, ecosystem conditions and welfare. The amount and form of a stressor are determinants in adverse outcomes. For example, short-term exposure to an ionizing radiation usually needs a relatively high dose to elicit acute harm, e.g., skin damage, but a much lower dose may be sufficient to cause chronic, long-term effects, for example, genetic or somatic effects, which lead to cancer [9]. Likewise, exposure to diethylstilboestrol (DES) can disrupt the endocrine and cause cancer [10], depending on the magnitude and duration of exposure, as well as receptor-specific information, like life stage, for example, children and pregnant women are often more vulnerable to exposures, given the proliferation of tissue development. Asbestos may cause various types of diseases, including asbestosis, mesothelioma, and lung cancer, depending on the size and type of fiber [11–15].

The waste manager needs knowledge of the pathways from the formation of any waste constituent to potentially resulting harm. This chapter introduces a number of these pathways linking stressors to adverse outcomes in receptors, which may be human, ecological, or materials. This pathway in its simplest form is:



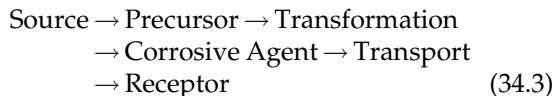
2 STRESSOR-RECEPTOR LINKAGES

A physical agent may be energy, as heat or electromagnetic fields. A chemical agent is a form of matter in any physical state. A biological agent is often a microbe, that is, a bacterium, fungus, or virus, but may also be larger species, for example, an opportunistic and invasive plant or animal. The source-to-receptor pathway is usually much more complex than pathway Eq. (34.1). It often involves chemical changes. The change may transform relatively nontoxic substances into a potent pollutant:



The transformation may occur anywhere in the environment, including within organisms.

An example of material damage is the emission oxides of sulfur and nitrogen that transform in the atmosphere into acids that corrode building materials (see Fig. 34.1). In this case, the stressor to receptor pathway would involve atmospheric transformation, that is, reactions to form acids, with the oxides as precursors to the stressor:



Material damage may not be among the stressor-induced problems that first come to a waste manager's mind. However, damage to materials increases societal costs, financial but also social and cultural.

Biology dictates that the process is even more complex than pathway Eq. (34.2), in that the environment may also be changed. For example, if a microbe or larger organism is introduced to an ecosystem, it may diminish or supplant the native species, which harms biodiversity. If the introduced organism is one in which the genetic material has been altered using recombinant deoxyribonucleic acid, the genetically altered organism may enter the mitochondria and

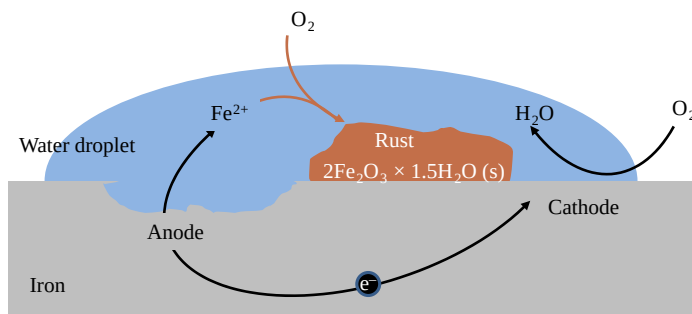


FIG. 34.1 Galvanic corrosion of iron. Corrosive action of metals often includes a galvanic process. That is, the liquid water reaching the metal surface either from precipitation or condensation becomes an electrolyte solution with two dissimilar metals. The positive ions (cations) are attracted to the negatively charged cathode and the negative ions (anions) are attracted to the positively charged anode. Thus rust is a redox reaction that begins with the formation of iron cations via half-reactions: $2\text{Fe}(\text{s}) \rightarrow 2\text{Fe}^{2+}(\text{aq}) + 4\text{e}^-$ and $4\text{e}^- \rightarrow 4\text{H}^+(\text{aq}) + \text{O}_2(\text{g}) \rightarrow 2\text{H}_2\text{O}(\text{l})$; leading to the full reaction: $2\text{Fe}(\text{s}) + 4\text{H}^+(\text{aq}) + \text{O}_2(\text{g}) \rightarrow 2\text{Fe}^{2+}(\text{aq}) + 2\text{H}_2\text{O}(\text{l})$. Note, (s)=solid; (l)=liquid; (aq)=aqueous; and (g)=gas. Reproduced with permission from D.A. Vallero, *Fundamentals of Air Pollution*, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, 999 pp.

nucleus of a wild species, that is, gene flow, thereby changing an ecosystem's structure or function [16–20]. In addition, the receptor is also potentially changing, for example, becoming more vulnerable to harm due to decreasing biodiversity of a habitat or a weakened immune system for an organism, including human. Thus the pathway is both biokinetic and biodynamic, that is, the agent and the environment are changing. If the second precursor is the weakening agent, the biokinetic/dynamic pathway is shown in Fig. 34.2:

Gene flow can affect an ecosystem by altering in interspecies interactions (e.g., predator-prey relationships), diversity, and productivity. Both ecosystem structure and function can be affected by gene flow. Such ecosystem effects may combine and increase in time and space, given the interconnections of ecosystems within biomes. [21] There is much debate about the likelihood

of gene flow in waste management and environmental scenarios. Genetically modified microbes are designed to be more efficient at breaking down recalcitrant chemical compounds [22, 23], which make them ideal for biostimulation and bioaugmentation of landfills and other bioreactors and waste disposal technologies. However, the waste manager must be aware of potential problems when selecting options that use genetically engineered organisms [20, 24, 25] (see Chapter 12).

3 ADVERSE OUTCOME PATHWAYS [26]

The life cycle of a pollutant begins with its formation. The waste manager's most common challenge is pollutant containment, with two waste basic containment objectives, that is, zero

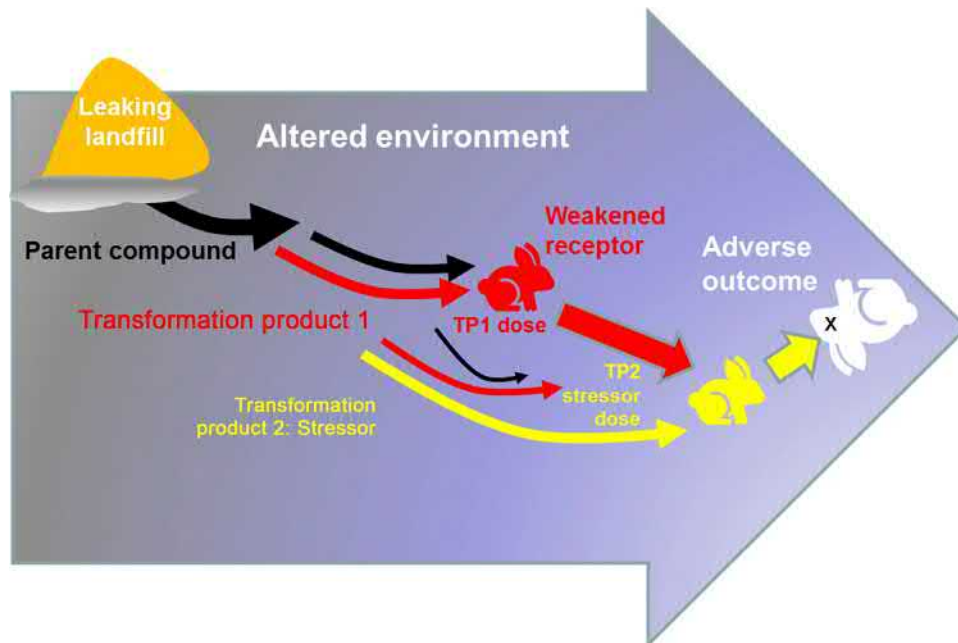


FIG. 34.2 Simple biokinetic/dynamic pathway of a released chemical compounds with two precursors. Width of arrows indicates concentration. The first precursor lathers the environment, that is, making it more hostile for beneficial organisms. The second precursor affects the receptor, for example, weakened immune system of an organism or decreased biodiversity of an ecosystem, before the ultimate adverse outcome caused by the stressor formed from the two transformations.

release for a specified period of time and a release amount below an allowable limit. The zero-release objective is required for certain substances, for example, biological or radioactive material. The specific time for zero release, that is, 100% containment, varies by pollutant. For a biohazardous wastes, the containment is up to the time the waste is thermally treated, for example, by autoclave or incinerator. Thus the containment extends to transport and treatment. Chemical wastes may need to be contained until the hazard no longer exists, for example, if a chemical is known to break down completely to nontoxic compounds after 2 weeks under most environmental conditions, the containment must be at least 2 weeks. However, the containment would likely be longer because in the real world conditions may differ. Thus the containment time must be lengthened as a factor of safety. The actual factors would be based on historical data and models. In the case of radioactive materials, the specified time may be thousands of years, according to the isotopic half-lives of the waste constituents. Thus the release of a pollutant in these situations is only unintentional, for example, improper maintenance or inadequate design for a rare seismic or meteorological event.

The second containment type, that is, controlled release, is commonly the basis for air and water standards. A very toxic compound would have a more stringent standard, that is, lower allowable mass or volume released per unit time, than a lesser toxic compound. For example, federal, state, or provincial permits and licenses would only allow for extremely low concentrations of a very toxic substance, for example, dioxins or cadmium, in the air emissions from a waste incinerator or the leachate from a landfill, compared to those for a less toxic element, for example, iron. The waste manager must know the allowable emission and discharge concentrations and types of sources who must request permits and licenses, since these vary among and within nations, states, provinces, counties, and municipalities.

The source-to-outcome framework depicted in Fig. 34.3 begins with the release showing the pathways within the environment, beginning with emission from a source, followed by transformations caused by physical, chemical, and biological processes in the environment. Contaminants or their transformation products travel within the environment where they are stored in various environmental media. The residence time within an environmental compartment may be but a few seconds (highly reactive compound with rapid-rate reaction) to many years (recalcitrant compound with slow-rate reaction). It is during these residence times that the receptor may come into contact with the pollutant [27, 28]. This contact becomes a dose, for example, mg per kg body weight per day ($\text{mg kg}^{-1} \text{ day}^{-1}$), as the receptor takes up and absorbs the pollutant. The adverse outcome only occurs when the dose reaches the target tissue, that is, this is the biologically effective dose [29]. For example, if a neurotoxin dose is the amount that reaches the brain and nervous system.

Stressors vary in the type and severity of hazards that they induce. The waste manager is encouraged to consult the databases, which exist for every box in Fig. 34.3. Although pathways often appear clear, there is considerable uncertainty in most. When assessing the hazards of most of these chemicals, researchers have had to rely on incomplete information and data. The incompleteness stemmed from limited studies and inadequate understanding of the mechanisms that lead to an adverse effect. In addition even when studies have been done, they can be proprietary and/or protected from wide availability as “confidential business information” [30]. In the United States, the National Research Council recently recommended an approach for intelligent testing of chemicals that has been a particularly important driver in harmonizing the understanding of these mechanisms. One of the needs to accomplish this is the consistent application of biological methods, including

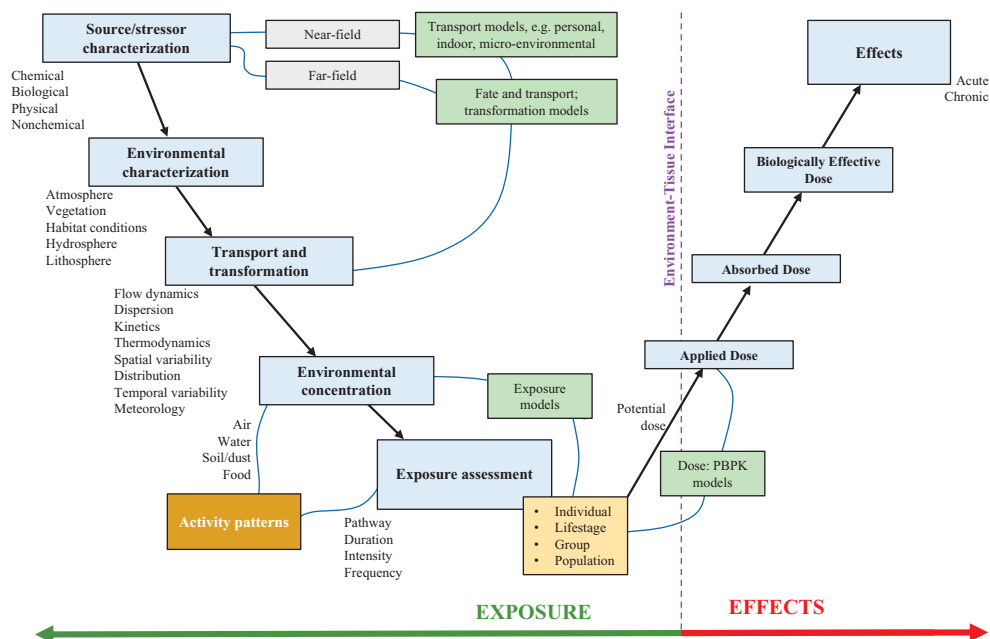


FIG. 34.3 Source-to-dose continuum. Exposure occurs after an agent is released into the environment until an adverse effect occurs (e.g., disease and disruption). Steps toward the right approach the adverse effect. Steps toward the left approach the source of the agent (e.g., air pollutant emission). Note: PBPK Models = physiologically based pharmacokinetic models. Models are shown in green. Yellow box is the focus of the exposure assessment. White box is the necessary psychosocial data to be combined with physical science data. Terms outside of boxes represent the physical, chemical, and biological data needed for each step. Modified from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Data from V. Dellarco, H. Gibb, S. McMaster, J. Orme-Zavaleta, D. Pahl, *Human Health Risk Assessment Research Strategy*. External Review Draft, DTIC Document, 1998; P.J. Liroy, K.R. Smith, *A discussion of exposure science in the 21st century: a vision and a strategy*, *Environ. Health Perspect.* 121 (4) (2013) 405.

innovative, robotic methods to increase the speed of in vitro assays of numerous chemicals [23, 31]. Testing methods rely on robotics, computational biology, and bioinformatics. [32].

Every biological system is complex. The complexity increases from the simplest single-celled organism to large diverse ecosystems. The boxes and arrows in Fig. 34.3 are not completely step-wise and linear, but involve physical motions, chemical reactions, biological processes and, for humans, psychosocial factors. These processes occur simultaneously and interact in space and time, at every level of biological organization. Mass and energy are exchanged constantly within and between cells, and at every scale,

cycling through organisms and the abiotic environment. A single chemical or organism undergoes biochemodynamics, from its release to its environmental fate. For example, if the metal and its compounds enter the food chain, they may alter ecosystem functions and structures, for example, the metals be included in nutrient cycling, that is, an example of ecosystem function, which may change the growth and survival of certain species, even changing the types of plants in the ecosystem, that is, an example of ecosystem structure. Although these are ecosystem processes, the metallic compounds in the plants may enter the diet of human populations when these plants are harvested and consumed.

The mechanisms that lead to environmental and human health effects usually interrelate. The process begins when the stressor is generated, followed by a release to the environment, that is, the source of the environmental stressor, and reaches and contacts the receptor, that is, person, organism, ecosystem, material, and so on, that receives the stress. The entire process continues until an adverse outcome occurs, that is, the “source-to-outcome” pathway. Fig. 34.4 illustrates domains of environmental research. If one is only concerned with exposure, the flow would end before dose. If one is concerned exclusively with hazard, the interest ends at environmental characterization. However, for comprehensive risk perspective, all domains are needed, with each process incorporating other, more specific pathways.

The steps in Fig. 34.4 are perturbations of the system, with responses at each level of biological organization and trophic state (see Fig. 34.5) [23]. The adverse outcome pathway (AOP) is a relatively new method to characterize the mechanisms that take place following an organism’s exposure to a substance that ultimately lead to cellular damage. Information is quite sparse regarding which critical events are most important in altered biological pathway, that is, what phenotypic changes occur, where the biological pathway is perturbed and disrupted, and how these disruptions affect the entire organism. [33]

The beginning of the source-to-outcome pathway can be direct, such as a spill or leak. The release may be in the form of a plug, intermittent, or continuous flow. The source may also be indirect or stepwise. For example, if a microbe is no longer contained and is released into the environment, the microbe could be the stressor of concern, for example, a pathogen. However, even if it is not pathogenic itself, it may release biological or chemical substances that are inherently toxic, for example, contain endotoxins and allergens. Thus in these cases, at least one additional step occurs between containment and exposure (see Fig. 34.6).

In its simplest conception, the AOP consists of an exposure to an agent, uptake within an organism (e.g., absorption), which results in a molecular initiating event (MIE) that leads to an adverse outcome (see Fig. 34.7). Although correct, this pathway requires numerous additional arrows and boxes between the initiating event and the outcome. Indeed, the MIE is followed by a sequence of key events (KEs), which are connected to the MIE and with other KEs in key event relationships (KERs). After this sequence, ultimately, an adverse outcome (AO) occurs; first in an organism, then to a larger population of organisms [34] (see Fig. 34.8).

Of course, the AOP is much more complicated than single chain of events and single outcome scenario depicted in Fig. 34.8 consisting of numerous simultaneous and sequential molecular, cellular, organ, organism, and ecosystem responses (see Fig. 34.9). Each of these responses is the result of numerous biological processes. The macromolecular interactions are the result of interactions between cellular receptors and ligands, DNA binding, and protein oxidation, for example. Note that “receptor” in this usage differs from the rest of this chapter, that is, it is the “lock” into which the ligand, that is, the “key” fits.

Organism-level responses include lethality, impaired development, and chronic diseases; whereas higher levels of biological organization can be structural (e.g., changes in climax species) or functional, for example, changes in nutrient cycling and photosynthesis [35].

Among the first type of adverse outcome considered for an AOP was skin sensitization. Tests attempt to show if a chemical substance will induce an allergic reaction following previous contact to that substance or a chemically similar substance [36]. The sensitization mechanistic pathways and intermediate steps have been somewhat well developed (Fig. 34.10). The skin sensitization example illustrates the key needs to characterize these pathways and depends on numerous types of information [37]:

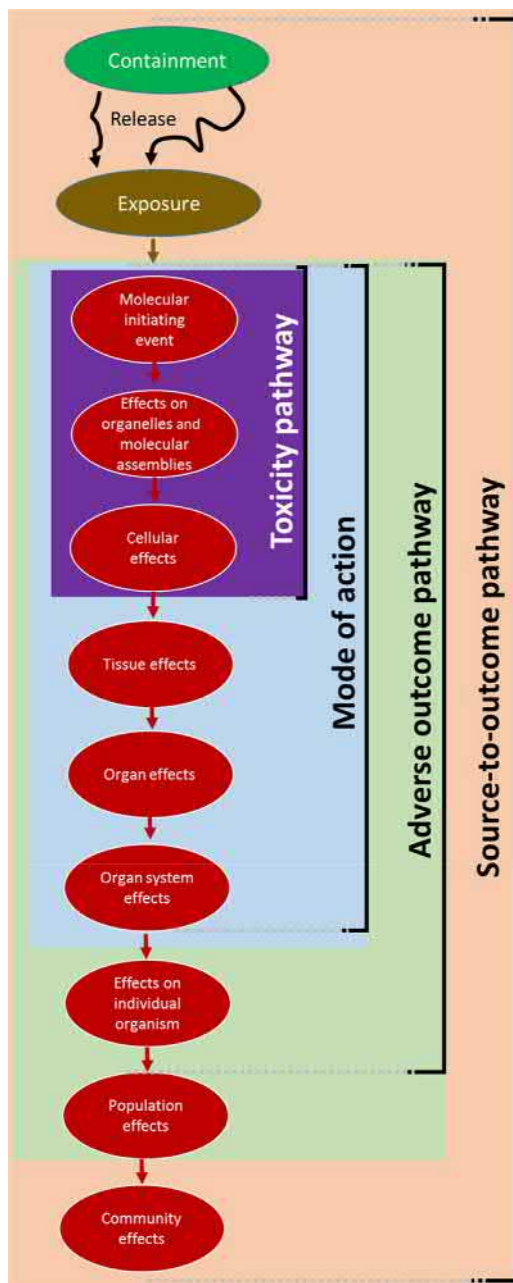


FIG. 34.4 Relationships among pathways leading to an adverse environmental outcome. *Reproduced with permission from D. Vallero, Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources. Academic Press, 2017. Modified from D. Vallero, Environmental Biotechnology: A Biosystems Approach. Elsevier Science, 2015; based on information from: D. Croft, et al., Reactome: a database of reactions, pathways and biological processes, Nucleic Acids Res. 1018 (2010); OECD, Report of the Workshop on Using Mechanistic Information in Forming Chemical Categories, ENV/JM/MONO(2011) 8, 2011.*

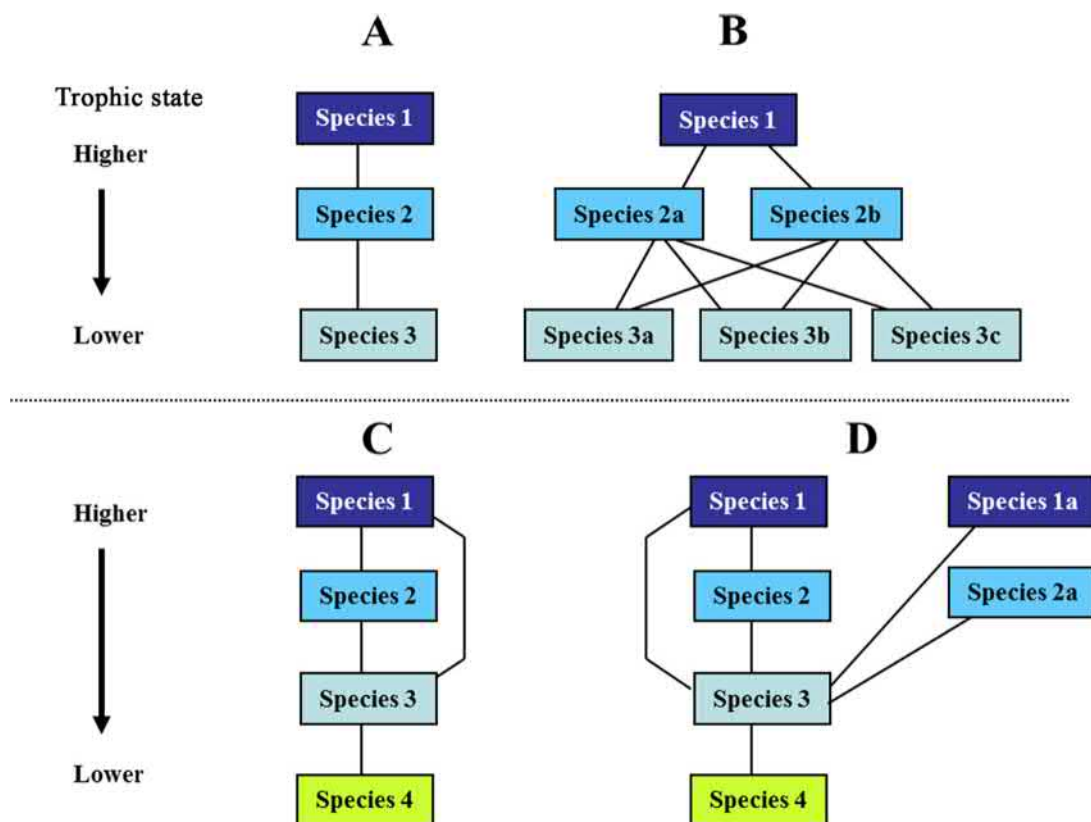


FIG. 34.5 Four exchanges of energy and matter from one trophic state to another, representing how stressors may move and transform among different levels of biological organization. Reproduced with permission from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Modified from D. Vallero, *Environmental Biotechnology: A Biosystems Approach*. Elsevier Science, 2015.

1. The degree to which the AOP is characterized is the AOP.
 2. The strength of linking initiating and other key events causally.
 3. The limitations in the evidence in support of the AOP.
 4. The AOP's specificity to certain tissues, life stages/age classes.
 5. The degree to which initiating and key events are expected to be conserved across taxa.
 6. The identification of chemicals that trigger and do not trigger the MIE.
 7. A solid understanding of the physicochemical and biological features that increase or decrease the probability of a chemical being associated with an AOP.
 8. The identification of similar key events caused by the agents that could tie them to a common AOP.
 9. The differences among the chemicals that could lead to subcategorization.
- Many AOPs converge on common biological targets, resulting in the presence of specific biomolecules and other compounds. These endogenous substances can serve as biomarkers of effect, that is, they can indicate that toxic effects are or may soon be underway in the organism [38].

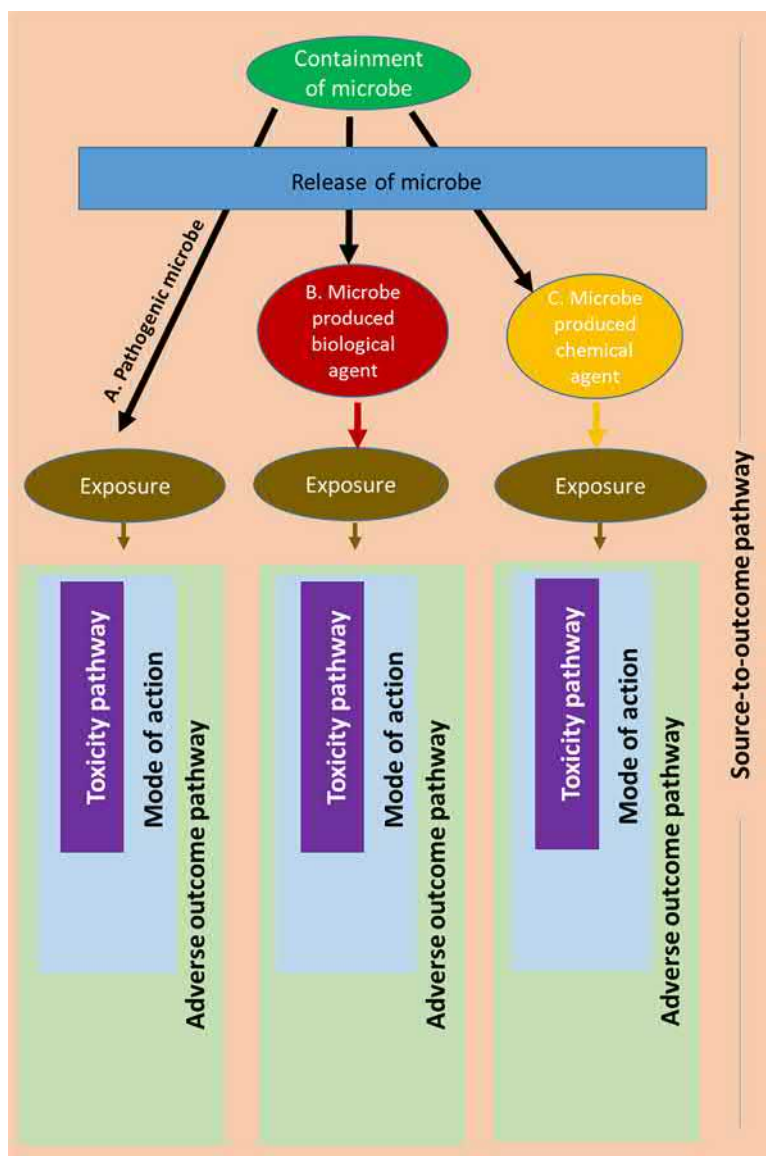


FIG. 34.6 After containment of a microbe is breached, the microbe may be (A) pathogenic and lead directly to an adverse outcome; (B) not pathogenic but releases a toxic biological agent (e.g., spore or cyst) that initiates a toxicity pathway; or (C) not pathogenic but releases a toxic chemical agent (e.g., a volatile organic compound to the air or an endotoxin endogenously to the blood). Each of these has its own pathways and mechanisms of action. *Reproduced with permission from D. Vallero, Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources. Academic Press, 2017. Modified from D. Vallero, Environmental Biotechnology: A Biosystems Approach. Elsevier Science, 2015.*

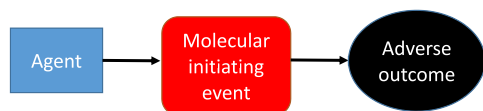


FIG. 34.7 Simplified view of the adverse outcome pathway, which is a conceptual framework of the logical sequence of events that lead to diseases, ecotoxic effects, and other adverse outcomes. Reproduced with permission from T.E. Allen, J.M. Goodman, S. Gutsell, P.J. Russell, Defining molecular initiating events in the adverse outcome pathway framework for risk assessment, *Chem. Res. Toxicol.* 27 (12) (2014) 2100–2112.

Many adverse outcome models depend heavily on in vitro and animal in vivo data to provide the quantitative information about these key events [39]. This approach can sometimes be complicated due to the body's ability to maintain homeostasis and tolerate relatively large perturbations. The challenge to modelers is to find the minimal level of perturbation that is necessary to significantly increase the likelihood of an apical effect and to characterize the

dose-response relationship at doses around this threshold level. For human health risk assessment, the reliance on animal data exclusively to parameterize these models can lead to problems when making quantitative predictions. For this purpose, animal studies should include a biomarker discovery component whereby biomarkers from accessible matrices (e.g., blood, urine) are quantitatively linked to these key events. These biomarkers can be defined as bioindicators to indicate this quantitative linkage to a key event. The bioindicators are now available for human biomonitoring and epidemiological studies to adjust the computational models for quantitative differences between animals and humans. Since these bioindicators are being used to link toxicity pathways to adverse outcomes, there is no need to perform this action for all chemicals. Once the quantitative relationship between the toxicity pathway perturbation and the adverse outcome has been established,

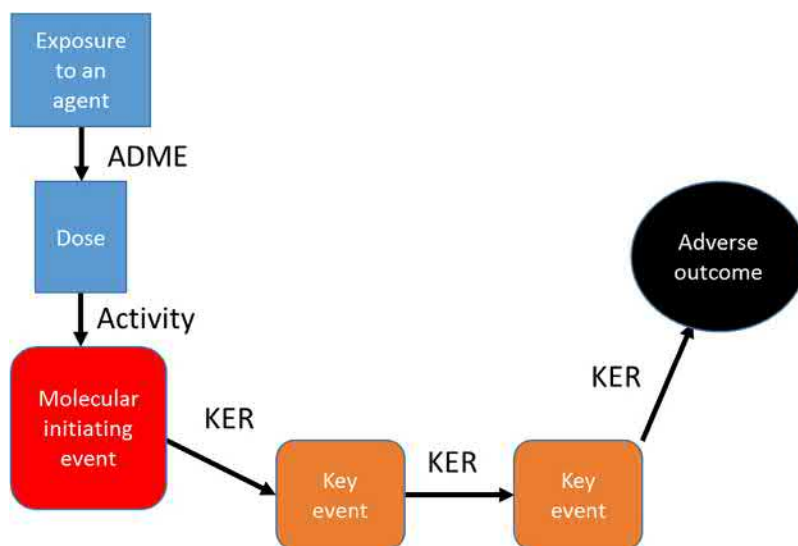


FIG. 34.8 An expanded view of an adverse outcome pathway (AOP), showing key events and key event relationships (KERs). Following absorption, distribution, metabolism, and elimination (ADME), a sufficient amount of the agent is available (i.e., not eliminated) to begin the AOP process. Reproduced with permission from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Modified from K.J. Groh, et al., Development and application of the adverse outcome pathway framework for understanding and predicting chronic toxicity: I. Challenges and research needs in ecotoxicology, *Chemosphere*, 120 (2015) 764–777.

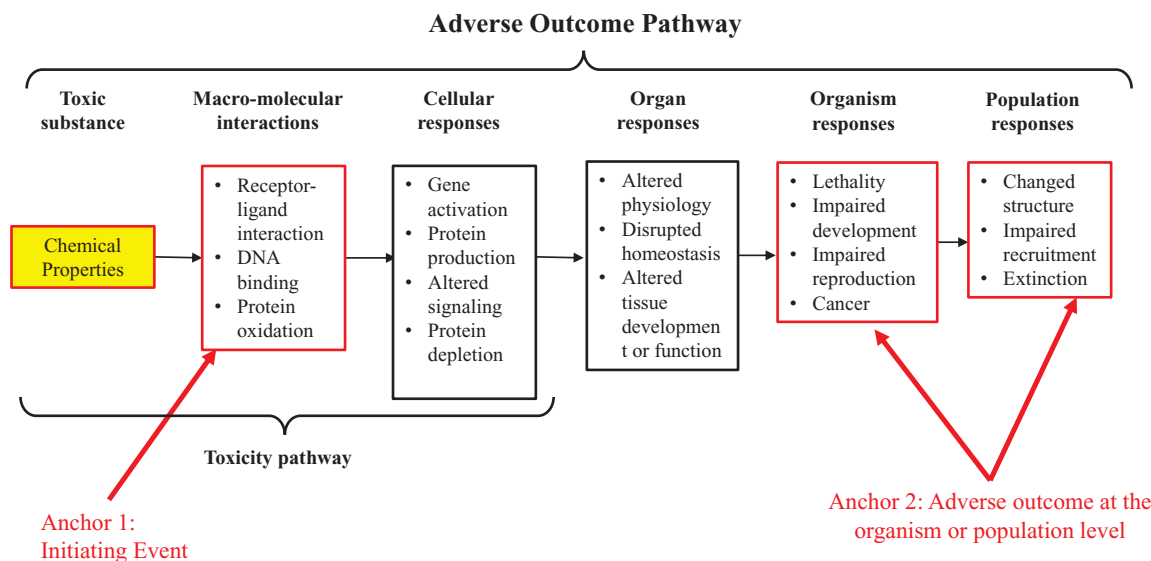


FIG. 34.9 An adverse outcome pathway (AOP) commences with a molecular initiating event in which an agent (in this case, a chemical compound) interacts with a biological target (Anchor 1), which causes a sequential series of higher order effects that ultimately lead to an adverse outcome (e.g., survival, development, reproduction, etc.; Anchor 2). Modified from T. Ankley, et al., *Adverse outcome pathways: a conceptual framework to support ecotoxicology research and risk assessment*, *Environ. Toxicol. Chem.* 29 (3) (2010) 730–741.

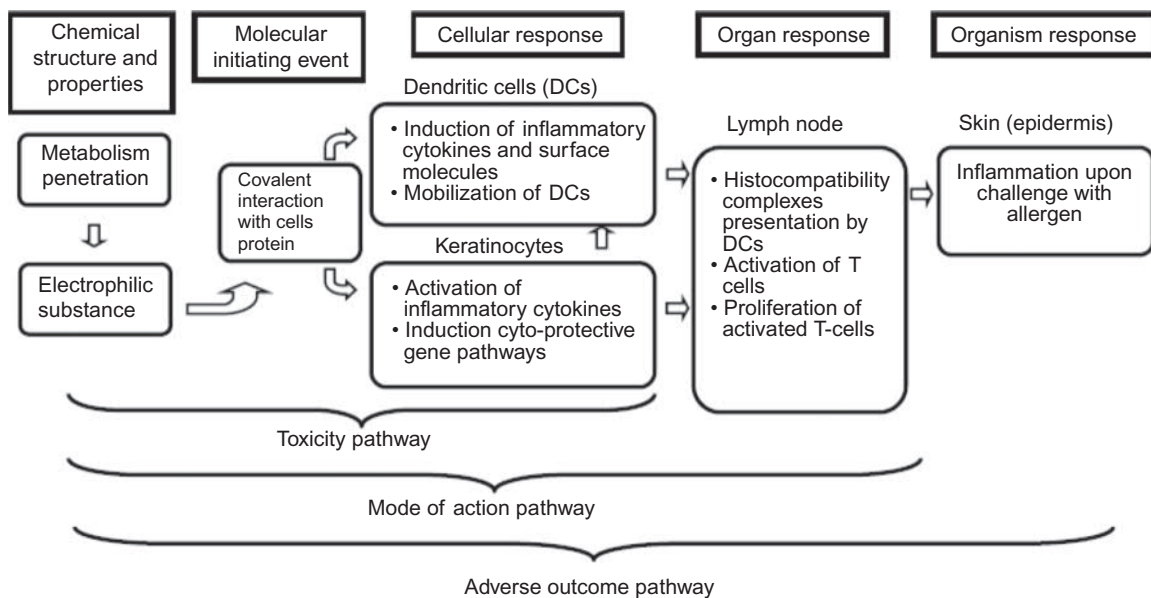


FIG. 34.10 Mechanistic pathways associated with skin sensitization. Reproduced with permission from OECD, *The Adverse Outcome Pathway for Skin Sensitisation Initiated by Covalent Binding to Proteins: Part 1: Scientific Evidence*, ENV/JM/MONO (2012)10/PART1, 2012.

predictions for new chemicals can be made based on the toxicity pathway perturbation alone.

The AOP concept is analogous to the “mode of action” (MOA) that was first developed in the 1980s to explain human health risks [40, 41] as part of the risk assessment process. Indeed, the AOP is an extension of the MOA. The MOA is an intrinsic aspect of an individual organism, whereas the AOP explicitly includes pathways leading to toxicity and extends them to higher levels, for example, populations and ecosystems. Thus the AOP takes a systems view of a disease or other adverse outcome, beginning with the molecular trigger and initiating event, wherein some process in the organism is perturbed and the toxicity pathway begins. This event is followed by numerous intermediate events until the adverse outcome occurs. The AOP can be applied to any level of biological organization, [42] from a single organism, to a specific habitat or subpopulation or even an entire population (see Fig. 34.11) [43].

To date, the AOP framework has been applied exclusively to the endogenous,

phenotypic changes in humans and other organisms individually. That is, the MOA includes not only the center component of Fig. 34.11, but all the intermediate events are included in the AOP framework. The AOP is a quantitative process, with each event characterized by various informatics and “omics” tools (examples are shown in the outer ring of Fig. 34.11). Thus this can be a very useful tool for early warning systems needed by regulatory authorities. For example, if an AOP shows that a particular genetic change has a chance of leading to an adverse outcome (e.g., an allergy in a human subpopulation or a loss of a sensitive species in an ecosystem), regulators may prohibit this use [43].

The AOP paradigm can and should be applied to levels of biological organization (see Fig. 34.12). For example, if an agent leads to cellular damage in organisms that serve as prey for organisms in a higher trophic state, the endogenous events are steps within a larger ecosystem. It is important to note that all the figures described up to this point are single stressor figures. However, in addition, toxicity and adverse

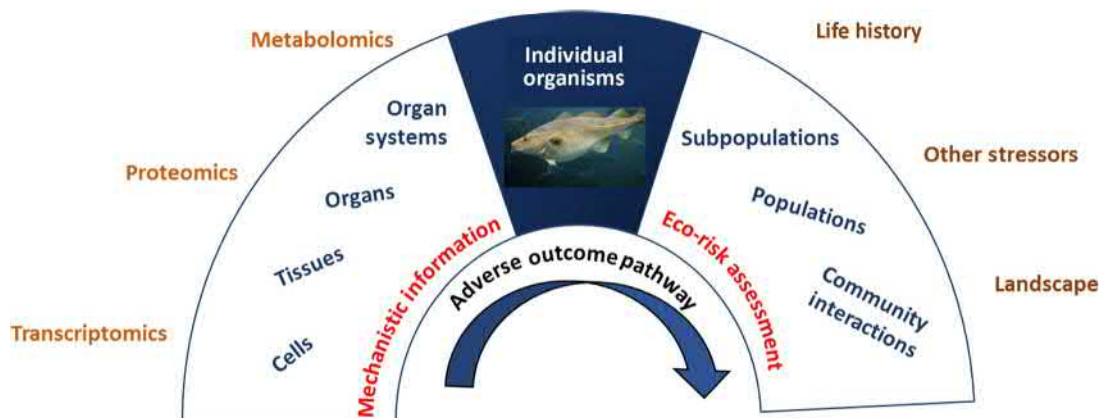


FIG. 34.11 Role of the individual organism in relating adverse outcome pathways (AOPs) to ecologically relevant levels of biological organization. The “omics” tools provide data to support identification of AOPs, whereas life history, landscape, and other biotic and abiotic stressors provide context to the population-level models built on the individual organism response. Reproduced with permission from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Modified from V.J. Kramer, et al., *Adverse outcome pathways and ecological risk assessment: bridging to population-level effects*, *Environ. Toxicol. Chem.* 30 (1) (2011) 64–76.

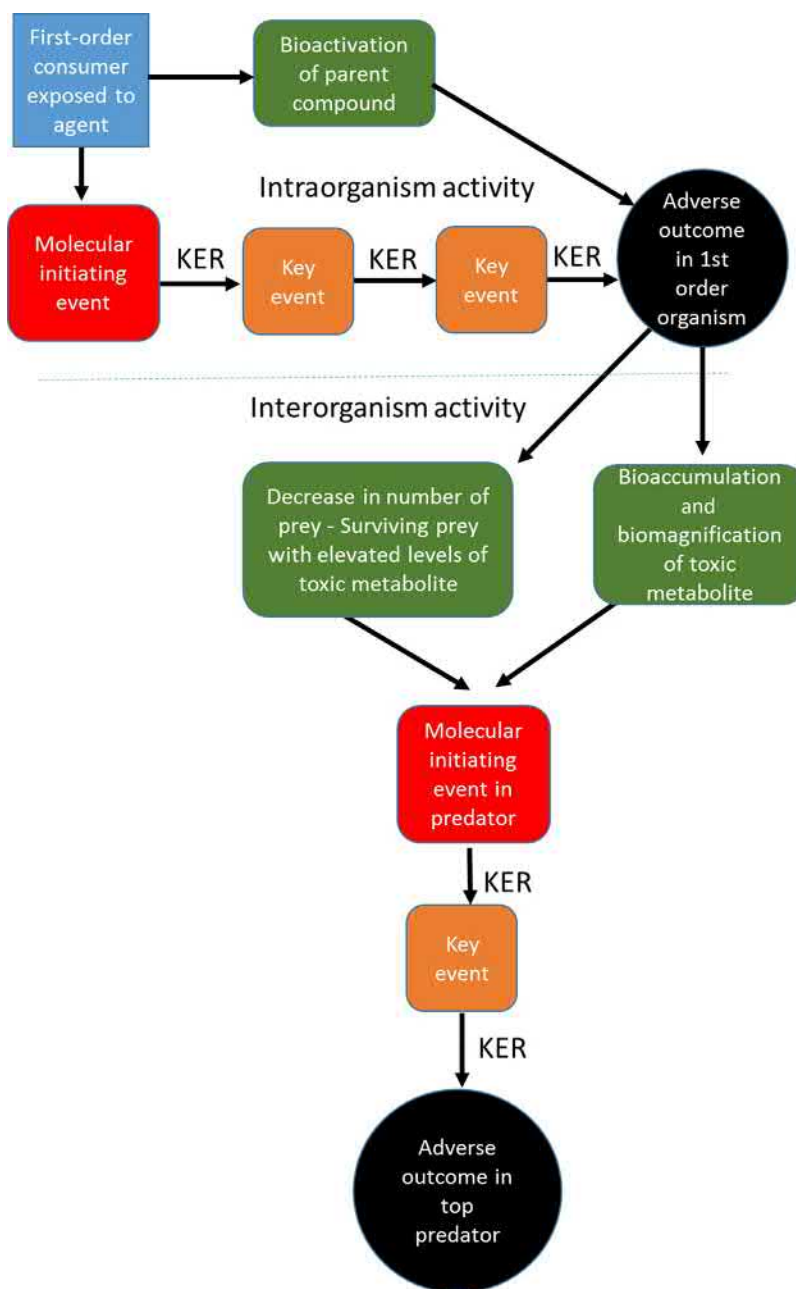


FIG. 34.12 Linked adverse outcome pathways (AOPs), in two levels of biological organization. The AOP plus other endogenous processes of the first-order producer lead to an AOP in the top predator. *Reproduced with permission from D. Vallero, Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources. Academic Press, 2017.*

outcome pathways initiated by the specific stressor in the lower trophic state organism, depicted in Fig. 34.12, there will be other, simultaneous pathways that are not be part of the AOP can still lead to problems. For example, in addition to the intraorganism AOP in Fig. 34.12, bioactivation may occur as the lower trophic state organism accumulates the parent compound and converts it to toxic forms. This toxic metabolite is transferred to the predator via the food chain. Thus the MIE in the predator may be affected by the exposure to the chemical and the decreased species abundance of its prey. Therefore endogenous AOPs must be combined with exogenous AOPs to present the entire AOP of ecosystem damage. Indeed, even within a single organism, numerous AOPs can occur simultaneously, so the multispecies setting of the ecosystem includes these, plus key events within food webs and chains that link the species.

4 BIOMONITORING

The waste manager may need to find information about a pollutant, but will find that all pathway datasets are incomplete in some way, for example, very little or nothing may be known about one or more of the AOP key events. Often, indirect measurement data are available. The waste manager needs a modicum of understanding these data, especially biomonitoring. Biomarkers are chemical concentrations of certain substances in fluids, tissue, and other biological substrates (see Figs. 34.13 and 34.14).

When a panel of urine and blood work is requested, the physician uses the chemical concentrations of various compounds to estimate a larger system, such as the presence of a disease or the functioning of the neural, immune, or endocrine system. For example, an elevated concentration of a liver enzyme may indicate a liver disease or even another disorder (i.e., the liver is working to clear out a toxic agent). Since it is an

indirect approach, the elevated enzyme could also be an indication of something other than disease in question (false positive), that is, the specificity of the biomarker to an effect. This could also be present in the absence of this enzyme in the blood (false negative), that is, the sensitivity to the biomarker. Thus a biomarker may indicate that an organism has become exposed to a causative agent (exposure biomarker; see Table 34.1) or that a disease or other adverse outcome is occurring (effect biomarker; see Table 34.2). Biomarkers may also be indicators of susceptibility, that is, their presence may indicate that one group of organisms is likely to be more likely to incur adverse effects than others when exposed to stressor. Susceptibility biomarkers may result from genetic factors (e.g., difference in how the body responds to an exposure to a chemical compound), nutritional status, lifestyle, health condition, and age [44].

Environmental biomonitoring datasets are becoming increasingly reliable and include a growing number of stressors and other substances useful in assessing ecosystem condition or determining pathways leading to xenobiotic body burdens in humans. Working backwards from biomarker data to possible sources is a special type of source apportionment, known as exposure reconstruction [45]. By analyzing concentrations of substances in tissue, the route that led to these concentrations can be modeled by retracing the pathway from the biomarker to potential sources (see Fig. 34.15). The reconstruction is an attempt to identify a reverse critical path that reflects the emergence of the condition, for example, that of an individual human or of an entire ecosystem.

5 WASTE PATHWAY EXAMPLE: TIRE CRUMBS

Waste managers are constantly looking for innovative ways to reuse and repurpose substances to keep them from entering the waste stream. These efforts often center around

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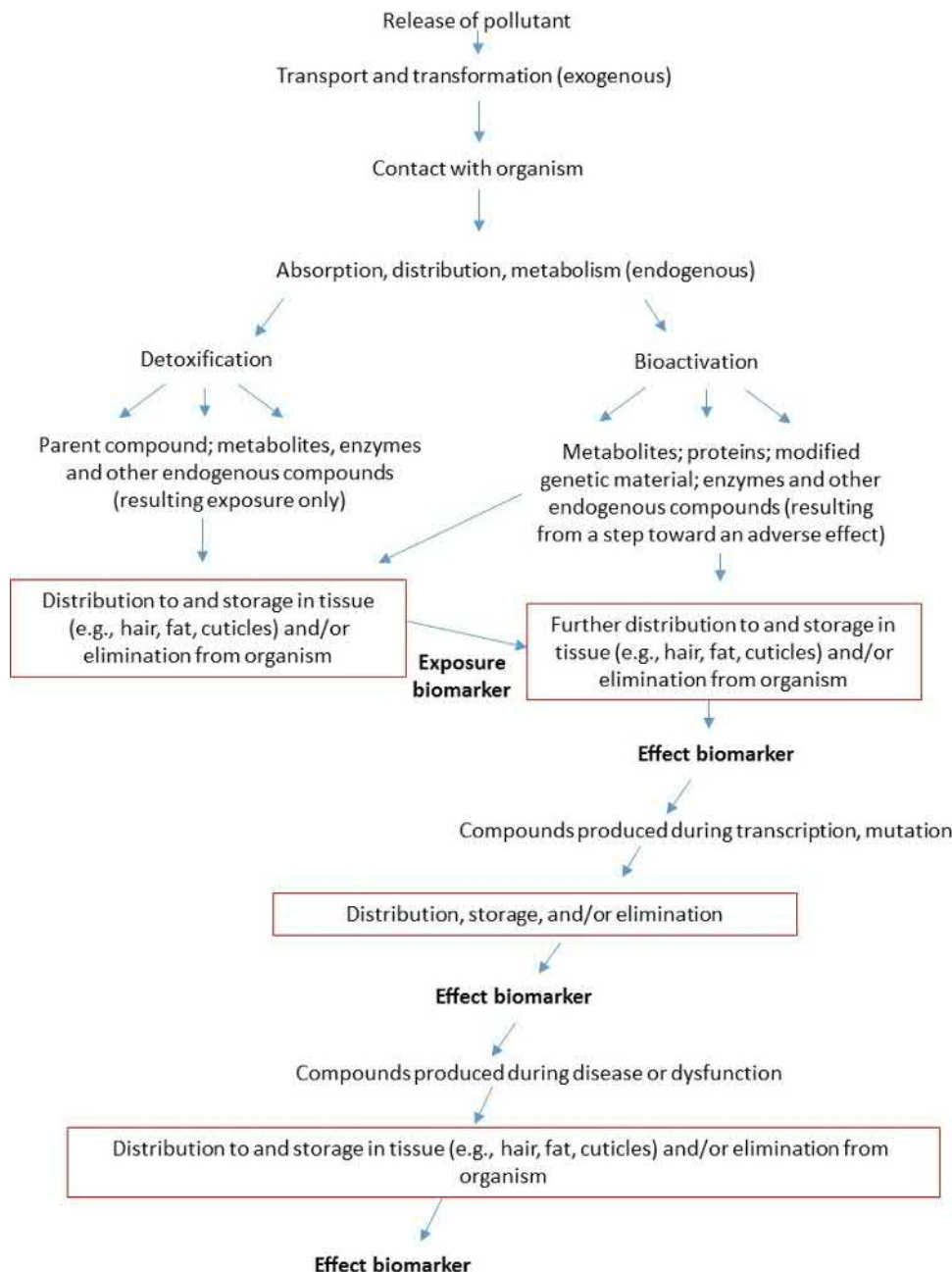


FIG. 34.13 Biomarkers can indicate an exposure to a stressor and/or indicate the effect induced by the stressor. After contact with the organism, the substances are taken up and absorbed. It may undergo distribution via the bloodstream to various tissue sites; be metabolized; stored in fats; and/or eliminated in urine, hair, breath, or feces. Substances found in these substrates can be biomarkers of exposure. Biomarkers of effect may change as the disease or other adverse effect develops. For example, a person may be exposed to a toxic substance, but if the substance is eliminated without initiating a toxic outcome, its presence in urine would merely be an exposure biomarker. If, however, a substance is released or stored during the life cycle of a disease, it may be an effects biomarker, with substances produced in varying quantities at different stages of the disease, or new substances produced at different disease stages. The effect biomarker does not have to be a metabolite of the stressor, but may be a compound produced by the organism in response to the presence of the stressor. *Reproduced with permission from D. Vallero, Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources. Academic Press, 2017. Data from D. Vallero, Environmental Biotechnology: A Biosystems Approach. Elsevier Science, 2015.*

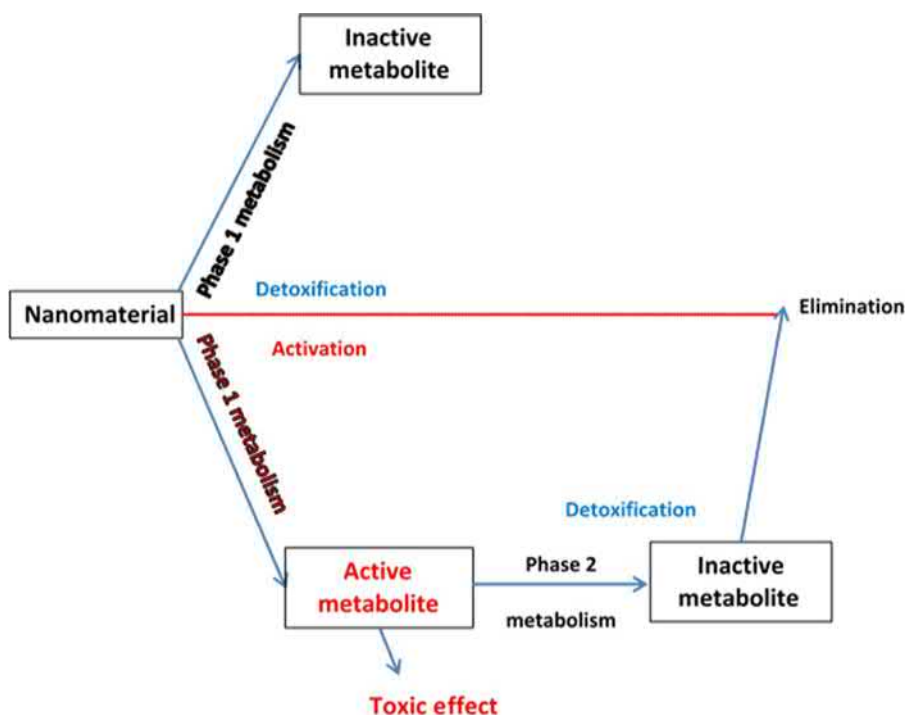


FIG. 34.14 Metabolic pathways of detoxification and bioactivation following uptake and absorption of a nanomaterial. *Reproduced with permission from D. Vallero, Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources. Academic Press, 2017. Modified from D.A. Vallero, Fundamentals of Air Pollution, fifth ed., Elsevier Academic Press, Waltham, MA, 2014, 999 pp.*

TABLE 34.1 Examples of Biomarkers of Exposure From Different Categories

Exposure Biomarker Category	Biological Matrix	Example Analytes	External Stressor
Chemical	Breath	Styrene (unmetabolized)	Styrene
Chemical	Feces	Bisphenol A (unmetabolized)	Bisphenol A
Chemical	Serum/urine	8:2 8:2 Polyfluoroalkyl phosphate ester	8:2 8:2 Polyfluoroalkyl phosphate ester (diPAP)
Metabolite	Blood	Styrene oxide	Styrene
Metabolite	Urine	BPA monoglucuronide	Bisphenol A
Metabolite	Serum/urine	Perfluorooctanoic acid	8:2 8:2 diPAP; other fluorinated alkyl acids
Endogenous surrogate	Urine/blood	Testosterone	Bisphenol A, other endocrine active compounds
Endogenous surrogate	Plasma	Butyrylcholinesterase inhibition	Toxicity due to acetylcholinesterase inhibition

Data from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Data from: U.S. Environmental Protection Agency. *Defining Biomarkers*, 2015. Available from: <http://www.epa.gov/pesticides/science/biomarker.html#susceptibility> (Accessed 20 February 2015).

TABLE 34.2 Examples of Biomarkers of Effect From Different Categories

Effect Biomarker Category	Biological Matrix	Example Analytes	Adverse Outcome/Biological Process
Bioindicator	Red blood cells	Acetylcholinesterase inhibition	Toxicity due to acetylcholinesterase inhibition
Bioindicator	Blood	Maternal triiodothyronine/thyroxine (T3/T4; thyroid hormones)	Neurological deficiency in offspring
Undetermined consequence	Blood/urine	Malondialdehyde	Oxidative stress
Undetermined consequence	Serum/urine	8-hydroxy-2'-deoxyguanosine	Oxidative stress
Exogenous surrogate	Blood	Lead	Neurological deficiency
Exogenous surrogate	Urine	3-phenoxybenzoic acid	Toxicity due to modulation of neuronal sodium channels
Exogenous surrogate	Urine	Para nitrophenol	Toxicity due to acetylcholinesterase inhibition

Data from D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*. Academic Press, 2017. Data from: U.S. Environmental Protection Agency, *Defining Biomarkers*, 2015. Available from: <http://www.epa.gov/pesticides/science/biomarker.html#susceptibility> (Accessed 20 February 2015).

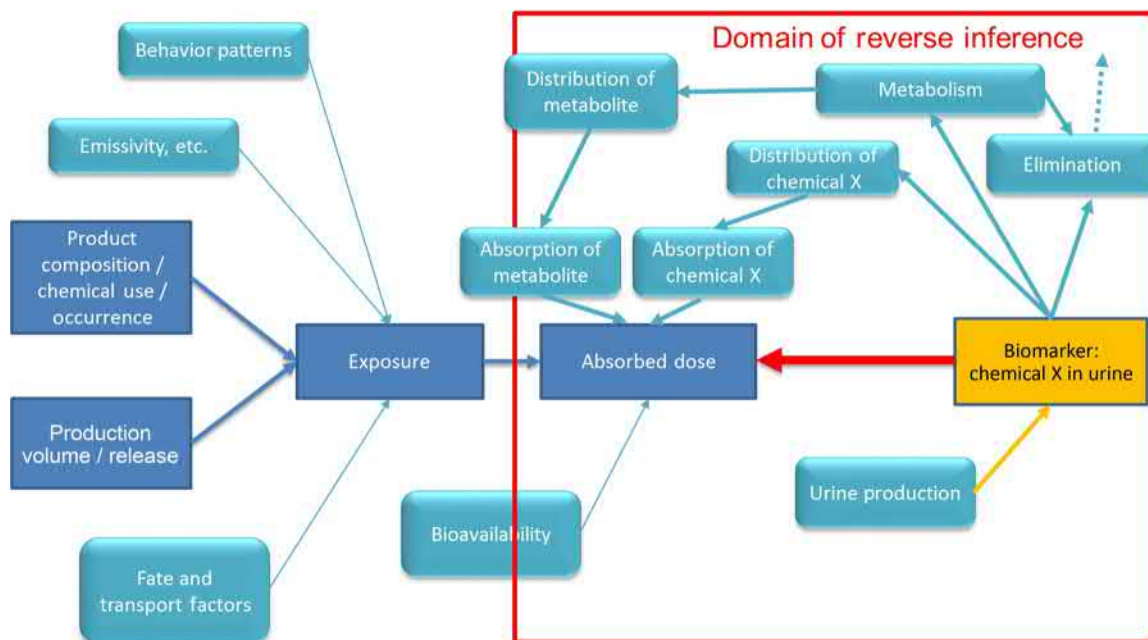


FIG. 34.15 Reverse toxicokinetic model. In this case, the domain of reverse inference is absorbed dose. The reverse modeling can continue back to the source, but this requires more data and algorithms to estimate exposure and source characteristics. Drawn by author based on data provided by W. Setzer, *Discussion on Reverse Toxicokinetic Model From a Biomarker Measurement*, U.S. Environmental Protection Agency, Research Triangle Park, NC, 2015.

function. For example, if a product or material is no longer useful as designed, there may be other uses for the all or some of the material elsewhere. This often requires some physical or chemical manipulation, for example, pelletizing plastics.

A recent example is the tire. Its original purpose is eliminated after some level of usage, for example, as indicated by depth of tread. For safety reasons, tires are replaced when tread becomes too shallow. This leaves millions of tonnes of tire material entering the waste stream. However, some of the qualities that lead to the materials may apply elsewhere. In the case of the rubber and other materials, the property of elasticity remains even after wear. After steel and fluff are removed the tire material, known as crumb rubber, becomes granular. After further physical processing, for example, cryogenics, granulation and sieving, and perhaps chemical treatment, the product remains pliable and elastic. This is attractive for industrial uses, such as pavement repair products. The revamped product has also been used extensively for safety and recreational reasons, for example, artificial turf and crumb rubber-laden playgrounds and fields. The pathway to the landfill is truncated. An estimated 40,000 tires must be shredded to cover a football field with artificial turf. Indeed, in 2013, over 40% of the tires, that is, almost 2 million tonnes, were recovered [46].

Unfortunately, health issues have been linked to crumb rubber, for example, concern about exposure to metals, volatile organic compounds (VOCs), and semivolatile organic compounds (SVOCs) [47–49]. This is particularly worrisome since the fields are highly used by vulnerable populations, for example, children and young women, who are susceptible to endocrine disruptors, which are commonly SVOCs like polycyclic aromatic hydrocarbons (PAHs). There has also been concerns about microbes, for example, *Staphylococcus aureus*, growing on the crumbs [46]. The pathway is a combination of physical, chemical, and biological mechanisms:

Tire (source) → Physical manipulation
 → Transformation into crumb
 → Turf additive → Turf on field
 → Transport of chemicals

(activity on field) → Receptor (child)
 → AOP (childhood disease)

(34.4)

The crumb rubber pathway also includes ecological steps, such as tire rubber constituents, for example, zinc, copper, barium, manganese, and aluminum, reaching waterways via storm sewers. These substances can be highly toxic to aquatic life [50]. Again, the pathway is a combination of physical, chemical, and biological mechanisms:

Tire (source) → Physical manipulation
 → Transformation into crumb
 → Turf additive → Turf on field
 → Transport of chemicals

(activity on field) → Runoff to sewers
 → Receptor (aquatic biota)
 → AOP (fish kill)

(34.5)

The studies conducted to date are not particularly helpful in deciphering the risks. To address this gap in the United States, the Office of Management and Budget approved a multiagency study to conduct field work to characterize how people may be exposed [46]. Indeed, the pathways show the trade-offs involved, including reducing wastes and added safety versus potential health and environmental adverse outcomes. This is but another example of the challenge of the waste manager to understand and explain the potential risks and benefits of an action.

6 CONCLUSIONS

Waste constituents follow various pathways that may lead to harm. Waste managers are served well by understanding these pathways

and using toxicity and other pathway data and information to inform waste management decisions.

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Waste Management Accountability: Risk, Reliability, and Resilience

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1 INTRODUCTION

The systems deployed by waste managers must sufficiently reduce risk, as well as be reliable and resilient. Reliability is the probability that the system will perform its intended function for a specified time and under

specified conditions [1, 2]. The systems must also be resilient, that is, able to return to the original form or state after being bent, compressed, or stretched or the ability to recover return to the desired state readily following the application from some form of stress [3–5].

1.1 Risk and Precaution

In evidence-based risk assessments, the onus is on the waste regulator to show that an action or agent is unsafe. Under this construct, which dominates U.S. health and environmental regulations, the agency may stop an action, for example, a new chemical being used in a product, only if it has sufficient information to support this decision. However, the agency usually may require the applicant to provide such information. Chemical risk assessment is a scientific approach to answering three basic questions [6]:

1. How much of chemical is in each environmental medium or compartment, for example, in the soil, water, air, carpet, walls, and so on?
2. What is the exposure to the chemical, that is, the amount of contact with a receptor in each medium and compartment?
3. How toxic is the chemical?

In the precautionary approach, any application is denied unless the applicant can provide sufficient information showing that the action or product is safe [7–11]. Unlike traditional risk assessments, which assume governance holds the burden of proof that something is harmless, the precautionary onus assumes that the burden of proof is entirely on those who anticipate the new action and if “reasonable suspicion” arises of a severe and potentially irreversible outcome, the action as proposed should be denied. This requires an objective, well-structured, comprehensive analysis of alternatives to provide a needed service, including a “no-action” if any of the alternatives are worse than doing nothing new.

Increasingly, evidence-based risk assessments are being augmented or even supplanted by precaution, especially if the decision involves a reasonable likelihood that an adverse effect is severe and irreversible [12]. The precautionary approach also calls for systems thinking and sustainable solutions. As discussed in Chapter 2, new screening models and tools are needed, including multicriteria decision analysis

(MCDA), which allows for the consideration of numerous variables, from various information sources. New ways to communicate risk and reliability include expert elicitation [13], as mentioned in Chapter 33.

Among the important gaps in data and tools needed for risk- and precaution-based decision making is more reliable means of estimating and predicting exposures to stressors. For example, human health characterization factors (CFs) in LCAs have benefited from improved hazard, especially toxicity, information [14]. Given that health risk is a function of hazard and exposure, both traditional risk assessment and LCA’s human health CF must be based on reliable exposure predictions [15]. For instance, in early life stages that, when used, could result in the formation and release of pollutants at some later stage, for example, eliminating wastes before they reach the household or changing waste collection approaches in early stages that prevent a future problems [16].

1.2 Chemical Screening

In the United States chemical risk assessment was codified for federal agencies in 1983 by the National Research Council (NRC) of the National Academy of Sciences [17]. A number of other NRC reports have since provided guidance on ways to assess risks of chemicals, including reports that highlighted the disparity between the rate of deployment of new anthropogenic chemicals and assessment of their potential risks to public health [18, 19]. Central to these evolving recommendations has been to replace the current practice of extensive animal-based characterization of chemical hazard, dose–response relationships, and extrapolation to human health with high-throughput in vitro tests, in silico models, and evaluations of efficacy at the human population level. In addition, human and ecosystem risk assessments require reliable approaches for exposure to these chemicals. Noting that risk is a function of both hazard and exposure, the NRC added

recommendations of how to advance the science that underpins environmental and human health risks [20]. Among these recommendations is the introduction of credible ways to screen and prioritize chemical substances before these chemicals become ingredients in products and components in articles that reach the marketplace. Such an exposure-based prioritization approach will depend on the high-throughput (HTP) and other tools that are not only rapidly deployed, but which are sound scientifically.

Meanwhile, systems sciences were rapidly advancing across the disciplines, for example, systems biology and systems chemistry. The systems approach has been employed in research and development, but also in practice. For example, engineering and biomedicine rely less on reductionist thinking, and increasingly call for translational science from one discipline to another. This requires that biological, chemical, and physical principles be meshed with the social sciences to explain why and how systems, including the human body and ecosystems, respond to stress. Engineers and physicians, of course, have long recognized that the real world cannot be reduced to the sum of its parts, and that failure analysis and disease diagnosis and treatment almost always has included “black boxes.” This is the quarry of systems thinking, that is, explaining how these black boxes work and apply these lessons to problems like solid waste.

Of the thousands of chemicals in the marketplace, many find their way into the waste streams discussed in this book. Some chemical compounds are inherently toxic, so extremely so. Some chemicals are nearly ubiquitous. They can be found in myriad manufacturing processes, consumer products, and in the environment. Some of these are particularly persistent and bioaccumulate in the environment and the food chain [21, 22]. When a chemical compound is both harmful *and* likely to reach people and ecosystems, they present special challenges.

Prioritizing these chemicals based on the harm they may cause is now an international concern [23–27]. However, such prioritization

is complex in that many chemicals may be toxic parent compounds that degrade into other compounds. Some of these may be even more toxic, persistent, and/or biodegradable than the parent compounds [28]. Even parent compounds that are not so toxic may degrade into toxic compounds. It must also consider the likelihood of contact with receptors. For example, a chemical used in an industrial process may be relatively safe within an industrial life stage if workers are wearing proper personal protection equipment, but in downstream life cycle stages may become problematic. During their residence time in solid waste, wastewater or other environmental media may allow them to combine and react with other substances within these substrates to become more hazardous. In nature and engineered bioreactors, for example, landfills, microbial populations help to degrade these substances [29–32], but can also generate increasingly toxic degradation products, that is, bioactivation [33, 34].

Most chemical screening, until relatively recently, has been based on the inherent properties of chemical. The screens were built from historical data from animal and epidemiological studies, often based on pure doses. Screening is now beginning to be based on both hazard, especially toxicity, and exposure information. For example, exposure prioritization can complement and/or be integrated into decision tools, such as the recently released CompTox dashboard [35], which includes individual chemical structures for over 700,000 compounds, and combines bioassay screening data, exposure modes, and product categories. Screening tools can be beneficial in identifying analytics associated with data-poor and emerging substance, for example, nanomaterials, by showing rankings of chemicals based on hazard and exposure potentials [13]. Such screening tools can also support the evaluation of a hypothetical portfolio of products (e.g., cleaning products and cosmetics) for various life stages of a product. A portfolio of products and an accompanying set of their chemical ingredients

can allow decision makers to rank products according to potential risk, including the likelihood of the formation and transformation of pollutants within solid waste [36].

2 ACCOUNTABILITY BASED ON RISK REDUCTION AND SUSTAINABILITY

Risk is generally understood to be the likelihood that an unwelcome event will occur. Risk is also investigated scientifically within well-established frameworks. Risk analysis addresses the factors that lead to a risk. The reduction of this risk (e.g., building containment structures around a landfill or enacting local rules to limit exposure to leachate) is risk management. Risk management is often differentiated from risk assessment, which is comprised of the scientific considerations, hazards, and exposures that make up a risk. As such, risk is a common metric for waste management. Both traditional risk management and precaution-driven management rely on scientifically credible risk assessments to underpin waste decisions [17].

One means of determining whether a pile of waste is being handled properly is to determine whether the handling process has exceeded some level of acceptable risk. This measure of risk, then, is an expression of operational success or failure. Too much risk means the waste management has failed society. Societal expectations of acceptable risk are mandated by the standards and specifications of certifying authorities. For wastes, this includes health codes and regulations, zoning and building codes and regulations, design principles, canons of professional engineering and medical practice, national standard-setting bodies, and standards promulgated by international agencies (e.g., ISO, or the International Standards Organization). In the United States, for example, standards can come from a federal agency, such as

hazardous waste landfill guidelines of the U.S. Environmental Protection Agency or material specifications for equipment, such as those of the National Institute of Standards and Testing (NIST). Standards are also articulated by private groups and associations, such as those from ASTM (formerly the American Society for Testing and Materials).

A useful measure of risk-based accountability is whether the risk presented by an alternative is “as low as reasonably practical” (ALARP), a concept coined by the U.K. Health and Safety Commission [37]. The range of possibilities fostered by this standard fall within three domains (see Fig. 35.1). In highest domain, the risk is clearly unacceptable. The bottom indicates generally acceptable risk. However, the size of these domains varies considerably on perspective. Reaching unanimity on the “acceptable” level of risk is nearly impossible, but consensus can be reached for most waste management actions.

The ALARP depends on a defensible margin of safety that is both protective and reasonable. Hence, reaching ALARP necessitates qualitative and/or quantitative measures of the amount of risk reduced and costs incurred with the design decisions. The ALARP principle assumes that it is possible to compare marginal improvements in safety, for example, marginal risk decreases, with the marginal costs of the increases in reliability [37]. Quantitating the ALARP regions is challenging. For example, defining benchmark doses and thresholds for “tolerability” is fraught with subjectivity. Indeed, the quantification may have to fall into ranges of protection, for example, distance to a container or filling point and the types of structures and activities allowed in the event of fugitive emissions, explosions, or other chemical releases. The more hazardous and the greater the likelihood of exposure, the further residences, offices, and other human structures must be sited [38].

To ascertain possible risks, the first step is to identify a general hazard (a potential threat) and then to develop a scenario of events that could

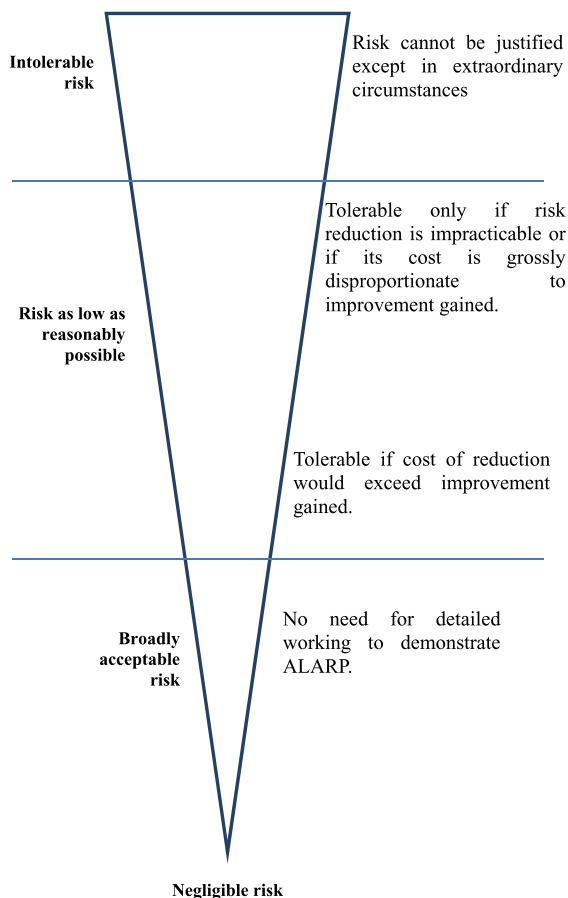


FIG. 35.1 Regions of risk tolerance. Source: *Health and Safety Executive, Guidance on ALARP Decisions in COMAH*, (2017). Available from: http://www.hse.gov.uk/foi/internalops/hid_circs/permissioning/spc_perm_37/.

take place to unleash the potential threat and lead to an effect. To assess the importance of a given scenario, the severity of the effect and the likelihood that it will occur in that scenario is calculated. This combination of the hazard particular to that scenario constitutes the risk.

2.1 Hazard

The hazard, that is, the physical, chemical, or biological agent of harm, must be matched

against the receptor's contact with that hazard, that is, exposure. The types of receptors range in scale and complexity, for example, the exposed receptor may be:

- an individual organism, for example, a human or other species;
- a subpopulation, for example, asthmatic children or endangered plant species in a habitat;
- an entire population, for example, all persons in a city, nation, or the world; or,
- a system, for example, a forest ecosystem.

Hazard is an inherent trait. Thus the hazard may occur before a waste is generated, such as a component of a manufacturing process. For example, if 1,1,1-trichloroethane (TCE) is used as solvent in a chemical processing plant, it may be hazardous to the workers because it is carcinogenic. It may also be hazardous if it finds its way to a landfill (in drums or in contaminated sawdust after a cleanup). Thus the decision to use a hazardous substance is seldom made completely on the basis of toxicity or other hazards. It is possible to avoid using a nearly non-toxic substance if the potential exposure is sufficiently high.

Making wastes less inherently hazardous is usually outside the individual waste manager's sphere of influence. Collectively, however, the waste management profession and its associations may call upon manufacturers and users of hazardous chemicals to use safer substances that provide the same function.

2.2 Exposure

The second component of the risk assessment is the potential of exposure to the hazard. In the previous TCE example, people can come into contact with the substance in occupational and environmental settings. Thus the exposure to TCE varies by activities (high for workers who use it, less for workers who may not work with TCE, but are nearby and breathe the vapors, and

even less for other workers). Usually, worker exposure is based on a 5-workday exposure (e.g., 8 or 10h), whereas environmental exposures, especially for chronic diseases like cancer, are based on lifetime, 24h per day exposures. Thus environmental regulations are often more stringent than occupational regulations when aimed at reducing exposure to a substance.

The explanation of exposure to chemicals and other agents requires a complete understanding of the chemical space, that is, physico-chemical descriptors that explain a mechanism or action, along with usage space, that is, how something is used. The integration of chemical and usage space can be thought of as exposure space.

In recent years, risk assessors have broadened the concept of exposure beyond a simple integration of chemical concentration with respect to time to one that includes biology, geography, and activity, that is, the exposome. Analogous to the genome, that is, a person's complete set of genetic material, the exposome is the person's complete biological makeup, activities, and environmental setting. A person, for example, can be exposed to physical, chemical, and biological agents differentially, depending on ethnicity, genetic predisposition and other biological makeup, life style (e.g., diet, habits, and exercise), and the time spent indoors, outdoors, at work, and the activities in these locations (environment). Collectively, these constitute that person's exposome [39].

2.3 Waste Risk Characterization

To ascertain possible risks from wastes, the first step is to identify a general hazard (a potential threat) and then to develop a scenario of events that could take place to unleash the potential threat and lead to an effect. This means not only is there a need for a sound characterization of what is in a waste, but how these waste constituents change in time and space and how they may act synergistically or

antagonistically within the waste. To assess the importance of a given scenario, the severity of the effect and the likelihood that it will occur in that scenario is calculated. This combination of the hazard particular to that scenario constitutes the risk.

The relationship between the severity and probability of a risk follows a general equation [40]:

$$R = f(S, P) \quad (35.1)$$

where risk (R) is a function (f) of the severity (S) and the probability (P) of harm. The risk equation can be simplified to be a product of severity and probability:

$$R = S \times P \quad (35.2)$$

The traditional chemical risk assessment paradigm (see Fig. 35.2) is a step-wise process. It begins with the identification of a hazard, which is comprised of a summary of an agent's physicochemical properties and routes and patterns of exposure and a review of toxic effects. The tools for hazard identification take into account the chemical structures that are associated with toxicity, metabolic and pharmacokinetic properties, short-term animal and cell tests, long-term animal (in vivo) testing, and human studies (e.g., epidemiology, such as longitudinal and case-control studies). These comprise the core components of hazard identification; however, additional hazard identification methods have been emerging that increasingly provide improved reliability of characterization and prediction.

Almost all wastes are mixtures. The chemical definition distinguishes mixtures from compounds. Within an environmental and public context, mixtures are combinations of constituents having unique hazards. Some of the constituents are relatively nontoxic, but are the substrates and matrices within which the hazardous constituents reside. These substrates and matrices may also make the wastes more dangerous. For example, relatively nonreactive substances may become bioavailable in fatty or

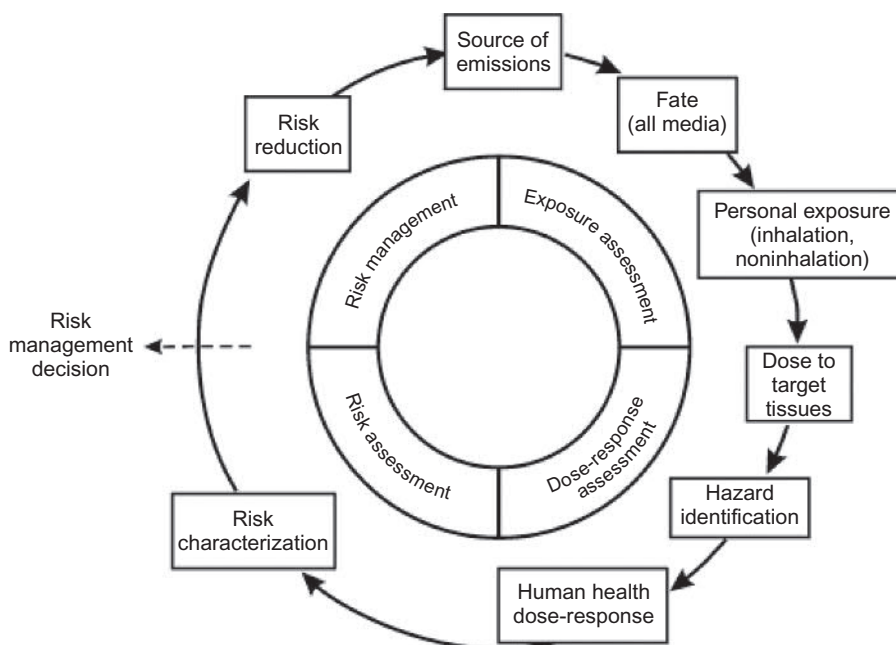


FIG. 35.2 Risk assessment and management paradigm as employed by environmental agencies in the United States. The inner circle includes the steps recommended by the National Research Council. *Source: National Research Council, Risk Assessment in the Federal Government: Managing the Process, National Academy Press, Washington, DC, 1983.*

low pH substrates, leading to highly toxic leachates. People and ecosystems are exposed to an array of compounds simultaneously [41]. Until relatively recently, toxicologists studied mixtures in a step-wise manner, adding substances one at a time to ascertain the response of an organism with each interaction. A number of recent toxicological studies have begun to look at multicomponent mixtures. From an exposure perspective, a mixture is actually a coexposure. A key question is how do the individual constituent's physical and chemical properties affect those of other waste constituents and vice versa? Are there additive, synergistic, or antagonistic effects when exposed to different substances simultaneously.

Thus characterizing the inherent properties of an individual constituent of a waste is but the first step in waste risk assessment. A number of tools have emerged to assist in this characterization.

Risk assessors now can apply biomarkers of genetic damage (i.e., toxicogenomics) for more immediate assessments, as well as improved structure-activity relationships (SAR), which have incrementally been quantified in terms of stereochemistry and other chemical descriptions, that is, using quantitative structure-activity relationships (QSAR) and computational chemistry. For the most part, however, health effects research has focused on early indicators of outcome, making it possible to shorten the time between exposure and observation of an adverse effect [42].

Wastes often possess nonchemical hazards. Notably biological and infectious wastes present hazards from biological agents that differ from those posed by chemical-laden wastes. Of course, biological agents range from beneficial to extremely hazardous. The Safety in Biotechnology Working Party of the European Federation of Biotechnology [43] has identified four risk

classes for genetically modified microbes, which can be applied to most microbes in wastes:

1. Risk class 1. No adverse effect, or very unlikely to produce an adverse effect. Organisms in this class are considered to be safe.
2. Risk class 2. Adverse effects are possible but are unlikely to represent a serious hazard with respect to the value to be protected. Local adverse effects are possible, which can either revert spontaneously (e.g., owing to environmental elasticity and resilience) or be controlled by available treatment or preventive measures. Spread beyond the application area is highly unlikely.
3. Risk class 3. Serious adverse local effects are likely with respect to the value to be protected, but spread beyond the area of application is unlikely. Treatment and/or preventive measures are available.
4. Risk class 4. Serious adverse effects are to be expected with respect to the value to be protected, both locally and outside the area of application. No treatment or preventive measures are available.

These classes indicate that even the safest microbes carry some risk and that with more uncertainty about an organism, one cannot assume it to be safe. That said, most microbes are not considered to be pathogenic, but certain human subpopulations are susceptible to hazards that may not exist for a large proportion of the population. Also, the risks may not be direct, such as a change induced by the release of organism into an environment where there are no natural predators. Thus risk scenarios include not only the effects resulting from the intended purpose of the environmental application, but also downstream and side effects that are not part of the desired purpose.

Like the hazard identification process for chemicals, the microbe is classified according to its inherent properties. It is in the next stage that environmental conditions are taken into

account; characterizing different responses to dose in different populations. Both the hazard identification and dose-response information are based on research that is used in the risk analysis. For microbes, the highest score for any one determines the overall risk class for environmental application.

Managing exposures to biological wastes (and any waste for that matter) must consider protecting the most vulnerable members of society, especially pregnant women and their yet-to-be-born infants, neonates, and immunocompromised subpopulations. Also, the exposure protections vary by threat. For example, adolescents may be particularly vulnerable to hormonally active agents, including many pesticides.

Risk can be extrapolated from available knowledge to similar chemical or biological agents with similar characteristics or to yet untested, but similar environmental conditions (e.g., a field study's results in one type of field extrapolated to a different agricultural or environmental remediation setting). In chemical hazard identification, this is accomplished by structural-activity relationships.

In the United States, ecological risk assessment paradigms have differed from human health risk assessment paradigms. The ecological risk assessment framework (see [Fig. 35.3](#)) is based mainly on characterizing exposure and ecological effects. Both exposure and effects are considered during problem formulation [44].

Interestingly, the ecological risk framework is driving current thinking in human risk assessment. The process shown in the inner circle of [Fig. 35.2](#) does not target the technical analysis of risk so much as it provides coherence and connections between risk assessment and risk management. In the early 1980s, risk assessment and management were conflated. A share of the criticism of federal response to environmental disasters, such as those in Love Canal, New York, and Times Beach, Missouri, belonged to the mixing of scientifically sound studies

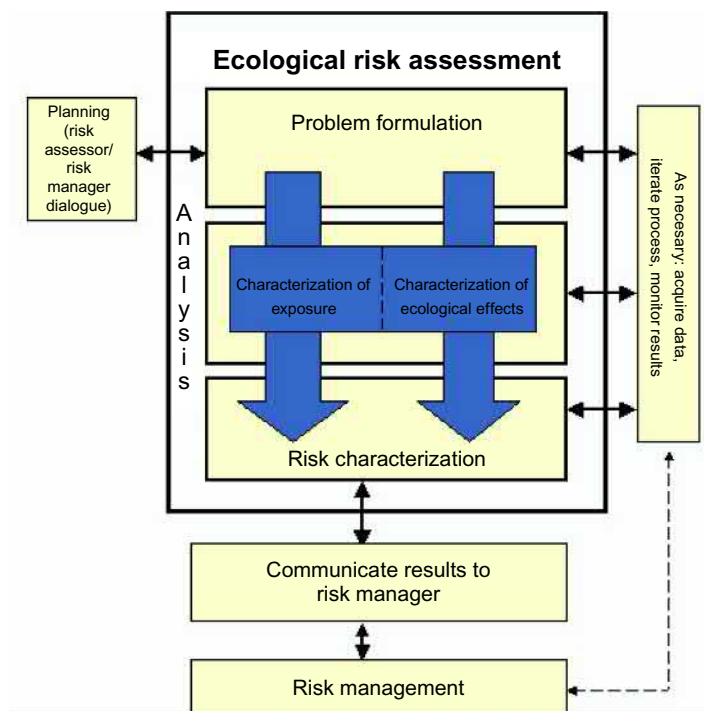


FIG. 35.3 Framework for integrated human health and ecological risk assessment. Source: U.S. Environmental Protection Agency, *Guidelines for Human Exposure Assessment*, 2018. Available from: <https://www.epa.gov/risk/guidelines-human-exposure-assessment>. Adapted from: US Environmental Protection Agency, "Framework for Ecological Risk Assessment, USEPA Risk Assessment Forum, Washington DC," EPA 630/R-92/0011992; World Health Organization, *Report on Integrated Risk Assessment*, World Health Organization, Geneva, Switzerland, WHO/IPCS/IRA/01/12, 2001; G.W. Suter II, *Ecological risk assessment*, CRC Press, 2016.

(risk assessment) with the decisions on whether to pursue certain actions (risk management) [45]. When carried out simultaneously, decision making may be influenced by the need for immediacy, convenience, or other political and financial motivations, as opposed to a rational and scientifically credible assessment that would underpin management decisions.

At some point, risk assessment and waste management must merge [46]. That is, the final step of the risk assessment process is referred to as "characterization" to mean that "both quantitative and qualitative elements of risk analysis, and of the scientific uncertainties in it, should be fully captured by the risk manager" [18]. The problem formulation should be applied in any risk characterization effort, both human and ecological, since it has the advantage of providing an analytic-deliberative process early on, since it combines sound science with input from various stakeholders inside and outside of the

scientific community. This can be helpful, not only in siting waste facilities, but also in nonstructural solutions to waste problems (e.g., waste minimization, changes in use scenarios, product substitution, and life cycle perspectives).

The term "hazard" has been used in chemical risk assessments to connote either intrinsic effects of a stressor or a margin of safety by comparing a health effect with an estimate of exposure concentration. Thus the term becomes ambiguous when applied to most nonchemical wastes, such as those encountered in biological systems.

Specific investigations are needed in the laboratory and field when adverse outcomes may be substantial and small changes may lead to very different functions and behaviors from unknown and insufficiently known physical, chemical, or biological agents. For example, a chemical compound may have only been used in highly controlled experiments with little or no information about how it would behave

inside of an organism. Often, the proponents of a product will have done substantial research on the benefits and operational aspects of the chemical constituents, but the regulatory agencies and the public may call for more and better information about unintended and yet-to-be-understood consequences and side effects [43].

Even when much is known, there often remain large knowledge gaps when trying to estimate environmental impacts. The bacterium *Bacillus thuringiensis*, for instance, has been applied for several decades as a biological alternative to some chemical pesticides. It has been quite effective when sprayed onto cornfields to eliminate the European corn borer. Thus it is likely to end up in several of the waste streams discussed in this book. The current state of knowledge indicates that this bacterium is not specific in the organisms that it targets. What if in the process, *B. thuringiensis* also kills honey bees? Obviously, this would be a side effect that would not be tolerable from either an ecological or agricultural perspective (the same corn crop being protected from the borer needs the pollinators). Furthermore, physical, chemical, and biological factors can influence these effects, for example, type of application of Downstream effects can be even more difficult to predict than side effects, since they not only occur within variable space, but also in variable time regimes.

3 DEFINING RISK

Engineers design systems to reduce risk and look for ways to enhance the reliability of these systems. Every waste manager deals directly or indirectly with risk and reliability. Waste systems must keep operating in rain or shine, no matter the conditions. Thus the third “R” is critical, that is, the systems must be sufficiently resilient to continue to meet the risk and reliability standards.

The discussion thus far may imply that the meaning of risk enjoys consensus. Disconcertingly

for most engineers and technologists who loathe ambiguity, the term “risk” has numerous meanings that depend on the context. Risk is defined by the International Organization for Standardization (ISO), as the effect of uncertainty on objectives and that such effect can be either positive or negative [47]. The Council of Supporting Agencies has adopted a similar core definition but holds that risks are negative effects and “opportunities” are positive effects. On the face of it, that may not appear to be particularly important; however, the ISO 31000 definition is commonly held within the technical risk management and infrastructure project management communities, including waste management.

The ability to communicate effectively can be hampered from the outset primarily because technical professionals often cannot communicate what risk means in terms that laypeople understand and also because they may not share a common definition among themselves. Although risk has some very precise definitions within a specific scientific community, for example, biomedical or environmental engineering, the various scientific disciplines have divergent concepts of risk (see Table 35.1).

Waste managers with engineering backgrounds usually express risk as an equation, which is the multiplicative product of the consequences of failure and the likelihood of failure. Within the public health and security community, risk is often understood to be synonymous with vulnerability, which is expressed as the multiplicative product of the consequences of failure, the hazard rate, and the likelihood of experiencing the hazard. In this sense, risk is indirectly proportional to reliability. Increasing a waste system’s reliability decreases risk. Environmental and public health risk, as mentioned, is the product of hazard and exposure [40]. There is a common thread running through all of these conceptions. We want to be aware of what has happened, is happening, and what may happen under various scenarios. Thus technical professionals may argue that any of these methods

TABLE 35.1 Comparison of Definitions of Risk in Technical Publications Versus Social Vernacular

-
1. Possibility of loss, injury, disadvantage, or destruction; to expose to hazard or danger; to incur risk of danger
 2. An expression of possible loss over a specific period of time or number of operational cycles
 3. Consequence per unit time = frequency (events per unit time) $\times$ magnitude (consequences per event)
 4. Measure of the probability and severity of adverse effects
 5. Conditional probability of an adverse effect (given that the necessary causative events have occurred)
 6. Potential for unwanted negative consequences of an event or activity
 7. Probability that a substance will produce harm under specified conditions
 8. Probability of loss or injury to people and property
 9. Potential for realization of unwanted, negative consequences to human life, health or the environment
 10. Product of the probability of an adverse event times the consequences of that event were it to occur
 11. Function of two major factors: (a) probability that an event, or series of events of various magnitudes, will occur, and (b) the consequences of the event(s)
 12. Probability distribution over all possible consequences of a specific cause which can have an adverse effect on human health, property, or the environment
 13. Measure of the occurrence and severity of an adverse effect to health, property, or the environment
 1. Probability of an adverse event amplified or attenuated by degrees of trust, acceptance of liability, and/or share of benefit
 2. Opportunity tinged with danger
 3. A code word that alerts society that a change in the expected order of things is being precipitated
 4. Something to worry about/have hope about
 5. An arena for contending discourses over institutional relationships, sociocultural issues, political and economic power distributions
 6. A threat to sustainability/current life styles
 7. Uncertainty
 8. Part of a structure of meaning based in the security of those institutional settings in which people find themselves
 9. The general means through which society envisages its future
 10. Someone's judgment on expected consequences and their likelihood
 11. What people define it to be—something different to different people
 12. Financial loss associated with a product, system, or plant
 13. The converse of safety
-

Source: S. Macgill, Y. Siu, *A new paradigm for risk analysis, Futures*, 37(10) (2005) 1105–1131.

define “risk.” Rather, these and many other methods do not *define*, but simply *express* risk.

Engineers and waste managers dislike uncertainty, so they extend the domain of the known domain to the domain of the lesser known. Historical data show that something failed under specified conditions and did not fail under different, specified conditions. If this is all the information with which to design, the gap between the two delineates the region of uncertainty. This is where factors of safety must be applied. Therefore risk is the effect of uncertainty on objectives, which translates into something unwanted. Indeed, environmental and public health agencies define risk as a probability of an *adverse outcome* (e.g., mortality, morbidity, loss of habitat, and diminished ecological diversity).

3.1 Modeling to Support Accountability

Risk management depends on models to estimate exposures. Such models range from “screening-level” to “high-tiered.” Screening models included generally overpredict exposures because they are based on conservative default values and assumptions. They provide a first approximation that screens out exposures not likely to be of concern [26, 48–52]. Conversely, higher tiered models typically include algorithms that provide specific site characteristics, time-activity patterns, and are based on relatively realistic values and assumptions. Such models require data of higher resolution and quality than the screening models and, in return, provide more refined exposure estimates [48].

Risk involves a stressor, a receptor, and an outcome. The stressor can be physical, chemical, or biological. Often, however, there is a cascade of stressor-receptor-outcomes. For example, if a water body’s temperature increases beyond some threshold value, the fish may die or fail to reproduce. The outcome, however, may involve multiple stressors and receptors. The fish outcome may be the result of the heat release

from a source, with the outcome of lowering dissolved oxygen, which is the real cause of the adverse fish outcome. In this case, the added heat (physical stressor) had a physical outcome (warmed aquatic system), which became a chemical stressor (lower dissolved oxygen) on a biological receptor (an individual adult fish’s inability to reproduce), which became an adverse ecological outcome (reproductive change in various fish genera), leading to a deleterious biological outcome (fish kill). This multiple-stressor/multiple-receptor scenario is further complicated, such as how physical, chemical, and biological stressors combine to lower the dissolved oxygen, when with the added heat and the release of organic matter into the water body, which was used as food by the aquatic microorganisms, using up the available oxygen, encouraging the growth of opportunistic species such as a dinoflagellate, for example, *Karenia brevis* (red tide) or *Pfiesteria piscicida*, which diminishes the population of prey fish. The loss of prey then harms every trophic state above, up to top carnivores. In this case, the stressors behave in first order (heat and organic matter), second order (microbes), and third order (lack of food), before the adverse outcome (loss of aquatic diversity).

Environmental stressors can be modeled in a unidirectional and one-dimension fashion. A conceptual framework can link exposure to environmental outcomes across levels of biological organization (Fig. 35.4). Thus environmental exposure and risk assessment considers coupled networks that span multiple levels of biological organization that can describe the interrelationships within the biological system. Mechanisms can be derived by characterizing and perturbing these networks (e.g., behavioral and environmental factors) [53]. This can apply to a food chain or food web model (see Fig. 35.5) or a model within an organism, for example, a human kinetic model (see Fig. 35.6), or numerous other modeling platforms.

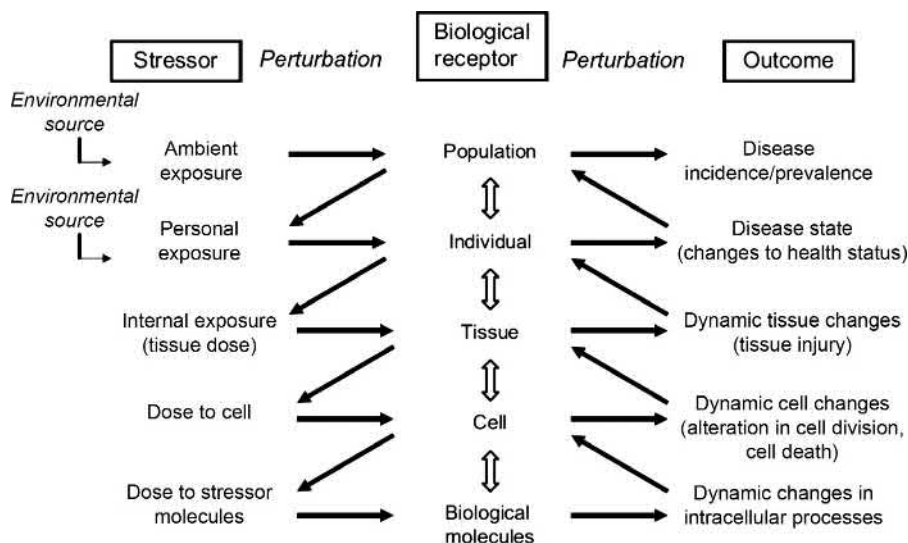


FIG. 35.4 Systems cascade of exposure-response processes. In this instance, scale and levels of biological organization are used to integrate exposure information with biological outcomes. The stressor (chemical or biological agent) moves both within and among levels of biological organization, reaching various receptors, thereby influencing and inducing outcomes. The outcome can be explained by physical, chemical, and biological processes (e.g., toxicogenomic mode-of-action information). Source: E.A.C. Hubal, et al., *Exposure science and the US EPA National Center for Computational Toxicology*, *J. Expos. Sci. Environ. Epidemiol.* 20(3) (2010) 231–236.

To assess the risks associated with a waste management decision, three questions must be asked:

1. What are the specific environmental concerns or harm that will or can occur?
2. What is the probability that the concerns will be realized or that harm will occur?
3. What are the adverse outcomes (e.g., to health and the environment) when the harm occurs, including how widespread in time and space?

These are deceptively simple questions. They are only easy to answer when an action is clearly wrong with no benefits whatsoever. For example, if a scientist simply wants to design a bandage that stays sterile during its entire use, few would oppose it. However, if the scientist used a neurotoxic metal like mercury to achieve this sterility objective, many would oppose such

research on the basis of its likelihood to cause other problems (e.g., to the central nervous system). However, the scientist may argue that he really needs such a bandage for a flesh-eating virus that seems to resist every other substance available for the bandage. Whether we agree, this is actually a question of short-term risks versus long-term advancement in medical and other societal knowledge. This is exactly what happened in introductions of species, such as kudzu and multiflora roses, which were only later found to have dramatically negative ecological impacts. If we could go back in time and have answers to the three questions above from our full knowledge of the implications observed in the field, these answers would have in all likelihood told the scientists and agricultural extension agents that the risks outweighed the benefits and the decision should be a “no go.”

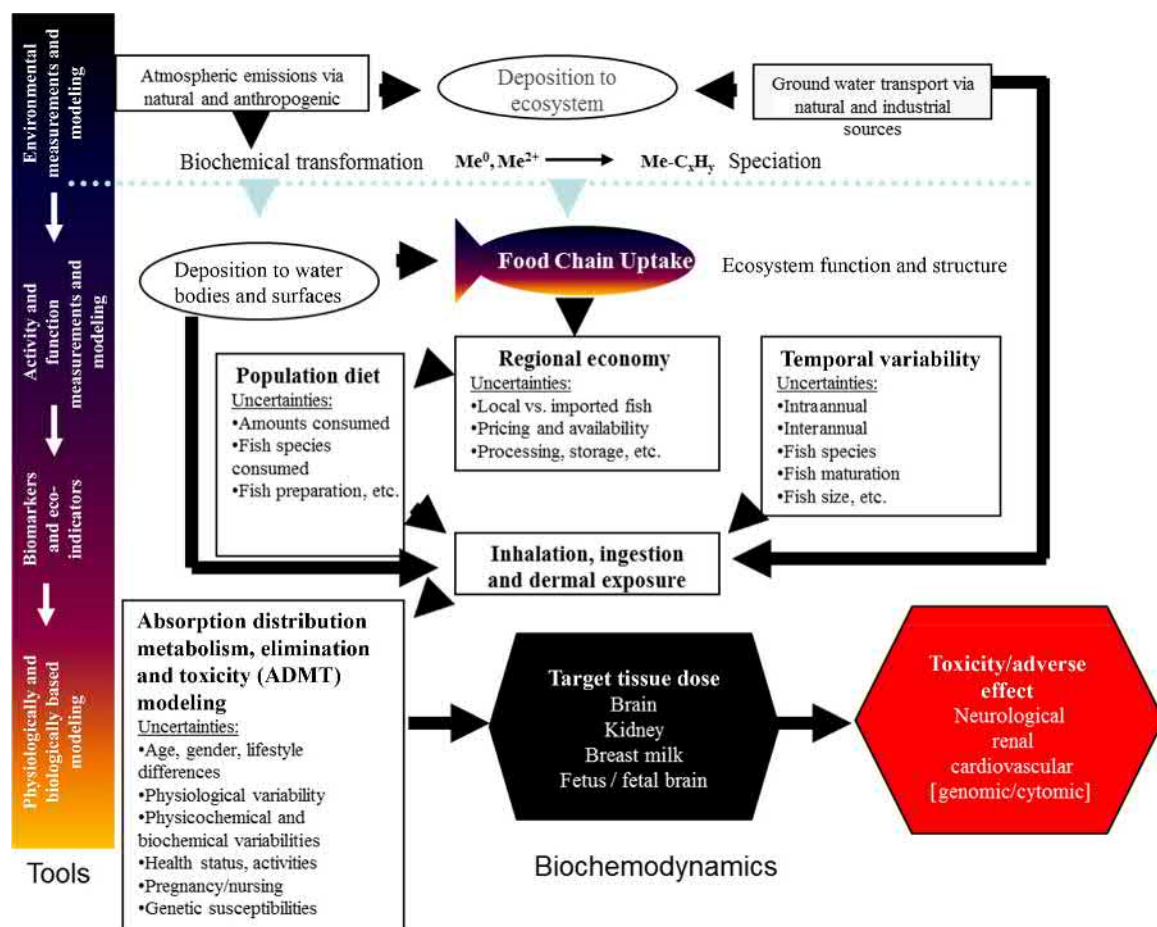


FIG. 35.5 Biochemodynamic pathways for a single, hypothetical metal (Me) in two oxidation states Me^0 and Me^{2+} , which is alkylated to $Me-C_xH_y$ within organisms. The fate is mammalian tissue. This depicts a combined human-ecosystem food web model. Various modeling tools are available to characterize the movement, transformation, uptake, and fate of the compound. Similar biochemodynamic paradigms can be constructed for multiple chemicals (e.g., mixtures) and microorganisms. *Adapted from D. Vallero, Environmental Biotechnology: A Biosystems Approach, Elsevier Science, 2015; D. Mangis, Discussion of exposure within the context of food chains, in: D. Vallero (Ed.), Research Triangle Park, NC, 2005.*

4 RISK-BASED DECISIONS

Having all the data needed for a *completely* informed risk decision is impossible. Scientific objectivity and humility dictate that risk assessors be upfront about uncertainties. The three questions can only be answered by looking for patterns and analogies from events that are

similar to the potential threat being considered. From there, scenarios can be developed to follow various paths to good, bad, and indifferent outcomes. This is known as a decision tree, which we will discuss later in this chapter. Risk assessment is a way to estimate the importance of each scenario and selecting the one with the most acceptable risk. This is not the same,

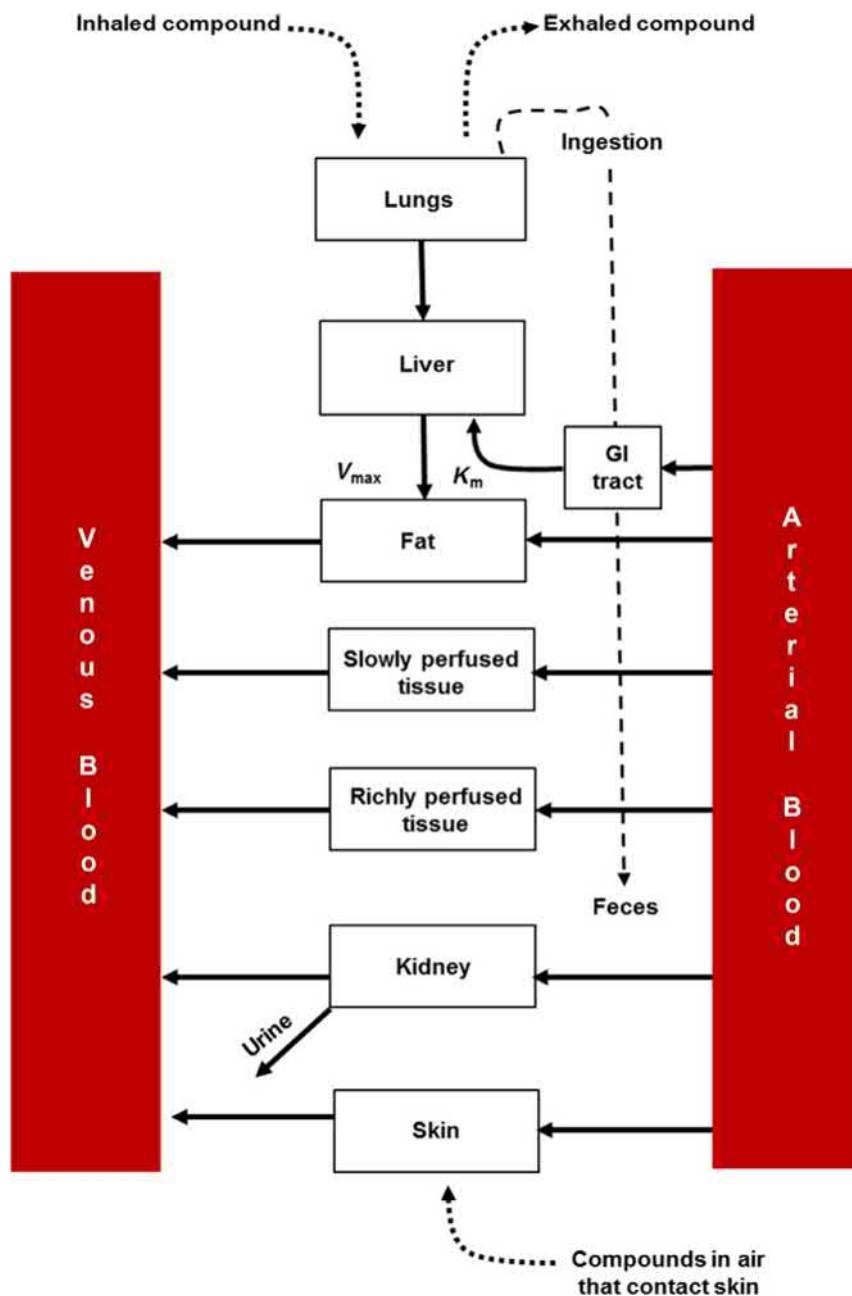


FIG. 35.6 Toxicokinetic model used to estimate dose as part of an environmental [40] exposure. This diagram represents the static lung, with each of the compartments (brain, carcass, fat, kidney, liver, lung tissue, rapidly and slowly perfused tissues, spleen, and the static lung) having two forms of elimination, an equilibrium binding process, and numerous metabolites. Notes: V_{max} is the maximum velocity at which the enzyme catalyzes a reaction, and K_m is the substrate concentration that is required for the reaction to occur at one-half of V_{max} . Adapted from S.S.I.D.A. Vallero, V.G. Zartarian, T.R. Mccurdy, T. Mckone, P. Georgopoulos, C.C. Dary, *Modeling and predicting pesticide exposures*, in: R. Krieger (Ed.), *Hayes Handbook of Pesticide Toxicology*, Elsevier Science, New York, NY, 2010, pp. 995–1020; X. Zhang, et al., *A physiologically based pharmacokinetic/pharmacodynamic model for carbofuran in Sprague-Dawley rats using the exposure-related dose estimating model*, *Toxicol. Sci.* 100(2) (2007) 345–359.

necessarily, as the one with the most benefits compared to risks, that is, a benefit-to-risk ratio or relationship, or benefit-to-cost ratio or relationship. However, this is indeed one of the more widely used approaches. The challenge is how to quantify many of the benefits and risks, since risk is a function of likelihood and severity of a particular adverse outcome (Eq. 35.2). As mentioned, environmental risk is often considered to be the product of the hazard and the exposure to that hazard.

4.1 Hazard Decisions

Anything with the potential to cause harm is a hazard. Some things are inherently hazardous, whereas others are hazardous in one scenario, but essential or desirable in another. Liquid water is a drowning hazard. Ice is a slipping hazard. Sharps, like syringe needles, are infection hazards. Pesticides are health hazards. At least a portion of the hazard is an intrinsic property of a substance, product, or process, that is, a concept of potential harm. For example, a biochemical hazard is an absolute expression of a substance's properties, since all substances have unique physical and chemical properties. These properties can render the substance to be hazardous. Conversely, Eq. (35.2) shows risk can only occur with exposure. So, if one walks on a street in the summer, there is little likelihood of slipping on ice is near zero. One's total slipping risk is not necessarily zero (e.g., a person could step on an oily surface or someone could throw ice in one's path). If not in a medical facility, one's infection risk from sharps may be near zero, but a person's total infection risk is not zero (e.g., people may be exposed to the same infection from a person sneezing in their office). If a person does not use pesticides, the pesticide health risk is also lower. However, since certain pesticides are persistent and can remain in the food chain, the person's exposure is not zero. Also, even if a person's pesticide exposure is

near zero, that person's cancer risk is not zero, since he or she may be exposed to other cancer hazards.

Of all the environmental hazards, the most attention has been devoted to toxicity. Other important environmental hazards are presented in Table 35.2. Hazards can be expressed according to the physical and chemical characteristics, as in Table 35.2, as well as in the ways they may affect living things. For example, Table 35.3 summarizes some of the expressions of biologically based criteria of hazards. Other hazards, such as flammability, are also important to environmental engineering. However, the chief hazard in most environmental situations has been toxicity.

4.2 Dose-Response Curves

The first means of determining exposure is to identify *dose*, the amount (e.g., mass) of a contaminant that comes into contact with an organism. The applied dose is the amount administered to an organism. The internal dose is the amount of the contaminant that enters the organism. The absorbed dose is the amount of the contaminant that is absorbed by an organism over a certain time interval. The biologically effective dose is the amount of the contaminants or its metabolites that reaches a particular "target" organ, such as the amount of a hepatotoxin (a chemical that harms the liver) that finds its way to liver cells or a neurotoxin (a chemical that harms the nervous system) that reaches the nerve or other nervous system cells. Theoretically, the higher the concentration of a hazardous substance or microbe that contacts an organism, the greater the response will be, that is, the expected adverse outcome. The pharmacological and toxicological gradient is the so-called dose-response curve (Fig. 35.7). Generally, increasing the amount of the dose means a greater incidence of the adverse outcome.

FOR REFERENCE PURPOSES ONLY

TABLE 35.2 Hazards Defined by the Resource Conservation and Recovery Act

Hazard Type	Criteria	Physical/Chemical Classes in Definition
Corrosivity	A substance with an ability to destroy tissue by chemical reactions	Acids, bases, and salts of strong acids and strong bases. The waste dissolves metals, other materials, or burns the skin. Examples include rust removers, waste acid, alkaline cleaning fluids, and waste battery fluids. Corrosive wastes have a pH of <2.0 or >12.5. The U.S. EPA waste code for corrosive wastes is "D002"
Ignitability	A substance that readily oxidizes by burning	Any substance that spontaneously combusts at 54.3° C in air or at any temperature in water, or any strong oxidizer. Examples are paint and coating wastes, some degreasers, and other solvents. The U.S. EPA waste code for ignitable wastes is "D001"
Reactivity	A substance that can react, detonate, or decompose explosively at environmental temperatures and pressures	A reaction usually requires a strong initiator (e.g., an explosive like TNT, trinitrotoluene), confined heat (e.g., salt peter in gunpowder), or explosive reactions with water (e.g., Na). A reactive waste is unstable and can rapidly or violently react with water or other substances. Examples include wastes from cyanide-based plating operations, bleaches, waste oxidizers, and waste explosives. The U.S. EPA waste code for reactive wastes is "D003"
Toxicity	A substance that causes harm to organisms. Acutely toxic substances elicit harm soon after exposure (e.g., highly toxic pesticides causing neurological damage within hours after exposure). Chronically toxic substances elicit harm after a long period of time of exposure (e.g., carcinogens, immunosuppressants, endocrine disruptors, and chronic neurotoxins)	Toxic chemicals include pesticides, heavy metals, and mobile or volatile compounds that migrate readily, as determined by the Toxicity Characteristic Leaching Procedure (TCLP), or a "TC waste." TC wastes are designated with waste codes "D004" through "D043"

From D. Vallero, *Environmental Biotechnology: A Biosystems Approach*, Elsevier Science, 2015.

TABLE 35.3 Biologically Based Classification Criteria for Chemical Substances

Criterion	Description
Bioconcentration	The process by which living organisms concentrate a chemical contaminant to levels exceeding the surrounding environmental media (e.g., water, air, soil, or sediment)
Lethal dose (LD)	A dose of a contaminant calculated to expect a certain percentage of a population of an organism (e.g., minnow) exposed through a route other than respiration (dose units are mg [contaminant] kg ⁻¹ body weight). The most common metric from a bioassay is the lethal dose 50 (LD ₅₀), wherein 50% of a population exposed to a contaminant is killed
Lethal concentration (LC)	A calculated concentration of a contaminant in the air that, when respired for 4h (i.e., exposure duration=4h) by a population of an organism (e.g., rat) will kill a certain percentage of that population. The most common metric from a bioassay is the lethal concentration 50 (LC ₅₀), wherein 50% of a population exposed to a contaminant is killed (air concentration units are mg [contaminant] L ⁻¹ air)

Source: M.D. Wood, K. Plourde, S. Larkin, P.P. Egeghy, A.J. Williams, V. Zemba, Valerie, I. Linkov, and D.A. Vallero, *Advances on a decision analytic approach to exposure-based chemical prioritization*, *Risk Analysis* (in preparation).

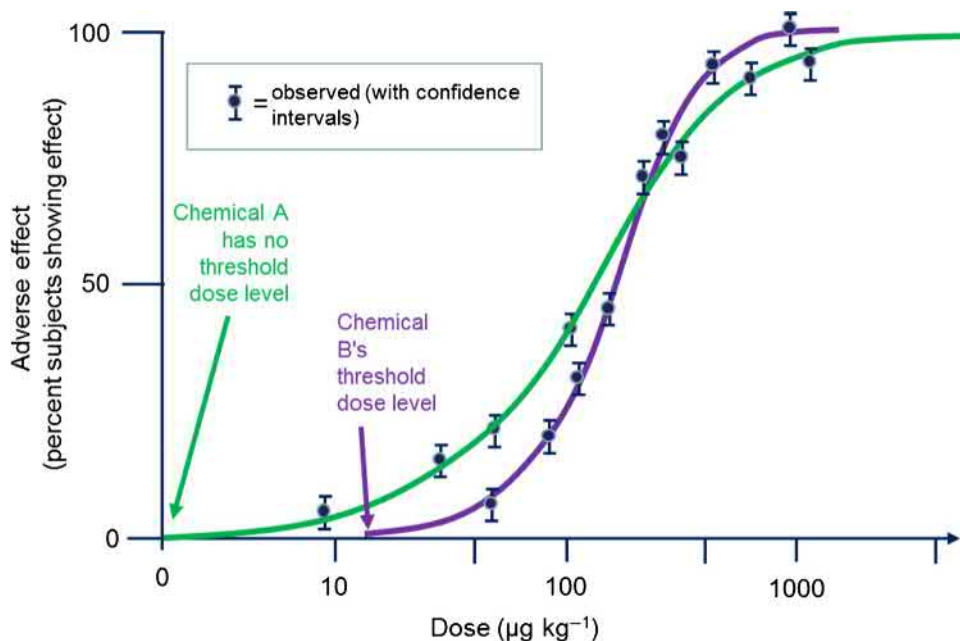


FIG. 35.7 Prototypical dose-response curves. Curve A represents the “no-threshold” curve, which predicts a response (e.g., cancer) even if exposed to a single molecule (“one-hit model”). As shown, the low dose end of the curve, that is, below which experimental data are available, is linear. Thus Curve A represents a linearized multistage model. Curve B represents toxicity above a certain threshold (no observable adverse effect level (NOAEL) is the level below which no response is expected). Another threshold is the no observable effect level (NOEL), which is the highest concentration where no effect on survival is observed ($\text{NOEL}_{\text{survival}}$) or where no effect on growth or reproduction is observed ($\text{NOEL}_{\text{growth}}$). Note that both curves are sigmoidal in shape because of the saturation effect at high dose (i.e., less response with increasing dose). Source: Adapted from D. Vallero, *Environmental Contaminants: Assessment and Control*, Academic Press, 2010.

Dose-response assessment generally follows a sequence of five steps [54]:

1. Fitting the experimental dose-response data from animal and human studies with a mathematical model that fits the data reasonably well;
2. Expressing the upper confidence limit (e.g., 95%) line equation for the selected mathematical model;
3. Extrapolating the confidence limit line to a response point just below the lowest measured response in the experimental point (known as the “point of departure”), that is, the beginning of the extrapolation to lower doses from actual measurements;
4. Assuming the response is a linear function of dose from the point of departure to zero response at zero dose; and,
5. Calculating the dose on the line that is estimated to produce the response.

The risk assessor can use published physical and chemical hazard characteristics for all of the chemicals used in the life cycle of a biotechnology. The process is useful, but may not be completely applicable to all wastes. For example, if a microbe in a waste is harmful to particular type of cell (e.g., a nerve), it may follow the steps just as a neurotoxic chemical. However, if the microbial modifications change microbial populations in an organism or in an ecosystem,

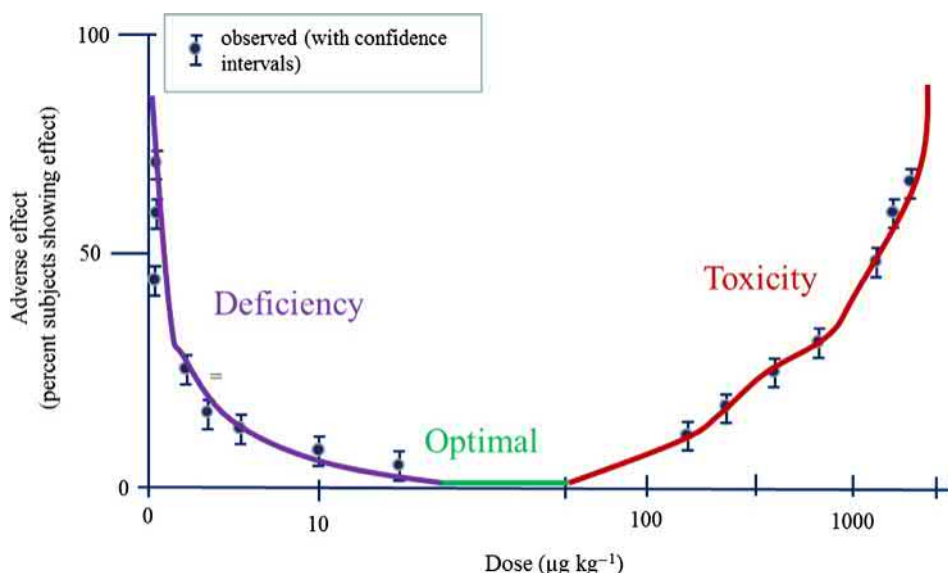


FIG. 35.8 U-shaped curve with dose regions of deficiency and toxicity. Between them is the optimal range, that is, sufficiently high to avoid deficiency and sufficiently low to avoid toxicity. This applies to nutrients and vitamins, as well as some metals, for example, trivalent chromium.

the dose-response may become much more complex than a single, abiotic chemical hazard.

The curves in Fig. 35.7 represent those generally found for toxic chemicals [15]. Once a substance is suspected of being toxic, the extent and quantification of that hazard is assessed. Actually, another curve could be shown for essential compounds like vitamins and certain metallic compounds. In such a curve (Fig. 35.8, the left-hand side (low dose or low exposure) of the curve would represent deficiency and the right-hand side (high dose or exposure) would represent toxicity, with an optimal, healthy range between these two adverse responses.

This step is frequently referred to as a dose-response evaluation because this is when researchers study the relationship between the mass or concentration (i.e., dose) and the damage caused (i.e., response). Many dose-response studies are ascertained from animal studies (in vivo toxicological studies), but they may also be inferred from studies of human populations

(epidemiology). To some degree, “Petri dish” (i.e., in vitro) studies, such as mutagenicity studies like the Ames test [16] of bacteria complement dose-response assessments, but are mainly used for screening and qualitative or, at best, semiquantitative analysis of responses to substances. The actual name of the test is the “Ames *Salmonella*/microsome mutagenicity assay” which shows the short-term reverse mutation in histidine-dependent *Salmonella* strains of bacteria. Its main use is to screen for a broad range of chemicals that induce genetic aberrations leading to genetic mutations. The process works by using a culture that only allows only those bacteria whose genes revert to histidine interdependence to form colonies. As a mutagenic chemical is added to the culture, a biological gradient can usually be determined. That is, the greater the amount of the chemical that is added, the greater the number of microbes and the larger the size of colonies on the plate. The test is widely used to screen for

mutagenicity of new or modified chemicals and mixtures. It is also a “red flag” for carcinogenicity, since cancer is a genetic disease and a manifestation of mutations.

The toxicity criteria include both acute and chronic effects, and include both human and ecosystem effects. These criteria can be quantitative. For example, a manufacturer of a new chemical may have to show that there are no toxic effects in fish exposed to concentrations below 10mgL^{-1} . If fish show effects at 9mgL^{-1} , the new chemical would be considered to be toxic.

A contaminant is acutely toxic if it can cause damage with only a few doses. Chronic toxicity occurs when a person or ecosystem is exposed to a contaminant over a protracted period of time, with repeated exposures. The essential indication of toxicity is the dose-response curve. The curves in Fig. 35.9 are sigmoidal because toxicity is often concentration dependent. As the doses increase the response cannot mathematically stay linear (e.g., the toxic effect cannot double with each doubling of the dose). So, the toxic effect continues to increase, but at a decreasing rate (i.e., decreasing slope). Curve A is the classic cancer dose-response, that is, any amount of exposure to a cancer-causing agent may result in an expression of cancer at the cellular level (i.e., no safe level of exposure). Thus the curve intercepts the x-axis at 0.

Curve B is the classic noncancer dose-response curve. The steepness of the three curves represents the potency or severity of the toxicity. For example, Curve B is steeper than Curve A, so the adverse outcome (disease) caused by chemical in Curve B is more potent than that of the chemical in Curve A. Obviously, potency is only one factor in the risk. For example, a chemical may be very potent in its ability to elicit a rather innocuous effect, like a headache, and another chemical may have a rather gentle slope (lower potency) for a dreaded disease like cancer.

With increasing potency, the range of response decreases. As shown in Fig. 35.9, a severe

response represented by a steep curve will be manifested in greater mortality or morbidity over a smaller range of dose. For example, an acutely toxic contaminant's dose that kills 50% of test animals (i.e., the LD_{50}) is closer to the dose that kills only 5% (LD_5) and the dose that kills 95% (LD_{95}) of the animals. The dose difference of a less acutely toxic contaminant will cover a broader range, with the differences between the LD_{50} and LD_5 and LD_{95} being more extended than that of the more acutely toxic substance.

5 UNCERTAINTY AND FACTORS OF SAFETY

Waste management is an endeavor steeped in uncertainty. The amount and the types of waste that need to be handled change in space and time. The adopted practices vary. What we know, or believe we know, is never 100% certain. One definition of risks embraced by many engineers is that it is the effect of uncertainty on our ability to meet our objectives. In this instance, the “effect” is the deviation from the “expected” outcome [4]. Of course, this begs the question, who is expecting the outcome? Furthermore, as we discussed in Chapter 33, it is very likely that there will be disagreements with the waste manager as to the objectives. Policy makers and the public may care most about waste collection efficiencies and simply “assume” that the waste manager is ensuring that the environment and public health are protected.

Waste management decisions fall into two broad categories [55, 56]. The first is a decision under risk; the second, a decision under uncertainty. This is but another example of a twist on the term “risk,” since a decision under risk is one where the probability of all possible outcomes is known. When these outcomes cannot be known or are only incompletely known, the decision is said to be under risk. Optimizing for best approaches to handling a waste depends on the amount and quality of available data to

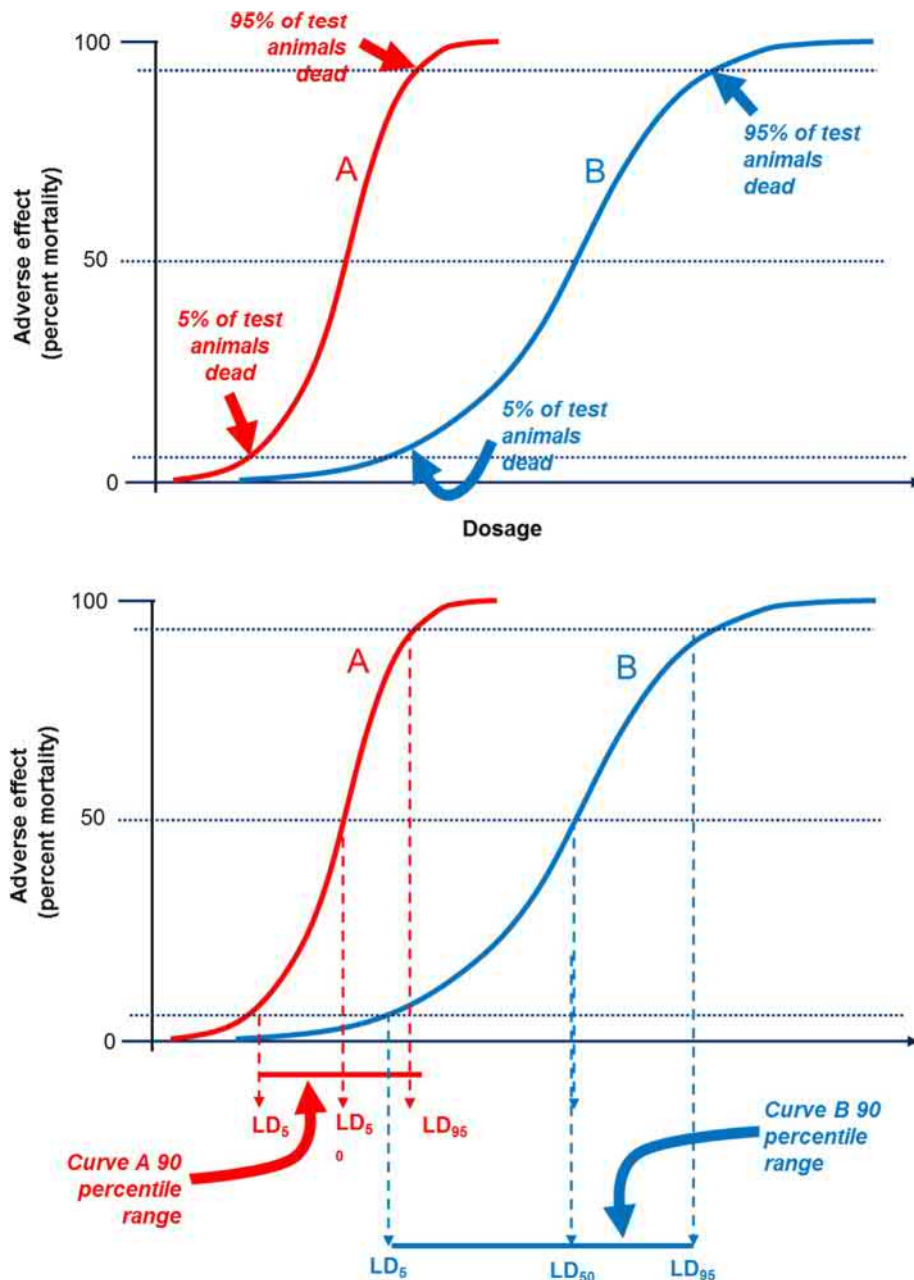


FIG. 35.9 The greater the potency or severity of response (i.e., steepness of the slope) of dose-response curve the smaller the range of toxic response (90 percentile range shown in bottom graph). Also, note that both curves have thresholds and that curve B is less acutely toxic based upon all three reported lethal doses (LD_5 , LD_{50} , and LD_{95}). In fact, the LD_5 for curve A is nearly the same as the LD_{50} for curve B, meaning that about the same dose, contaminant A kills nearly half the test animals, but contaminant B has only killed 5%. Thus contaminant A is much more acutely toxic. Source: D. Vallero, *Translating Diverse Environmental Data Into Reliable Information: How to Coordinate Evidence From Different Sources*, Academic Press, 2017.

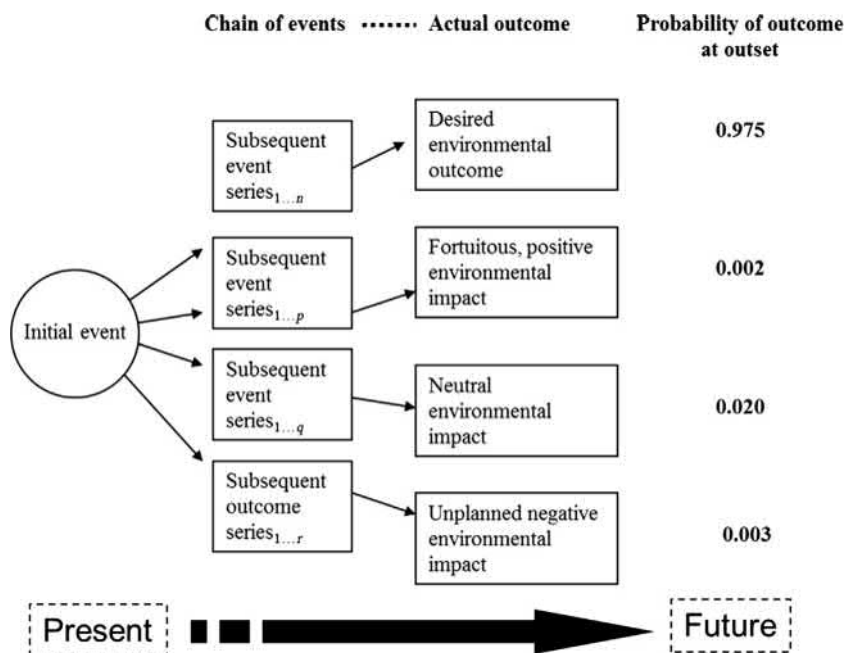


FIG. 35.10 Hypothetical example of an event tree representing decision under risk (fictitious data). Source: D.A. Vallero, T.M. Letcher, *Unraveling Environmental Disasters*, Newnes, 2012.

construct an event tree, that is, probability that each possible outcome can be drawn (see Fig. 35.10). Often optimization is less about selecting the “good” versus “bad” options, but about the “good enough, with fewer side effects” versus “not good enough, with too many side effects.” Typically, even the best alternatives can come with additional costs and risks. For example, increasing the desired beneficial outcomes can simultaneously increase detrimental outcomes (see Fig. 35.11). Obviously, identifying every contributing event is an impossible task for all but the simplest decisions; so, such event trees often include very broad assimilations of possible outcomes. Even if there is a wealth of information about possible outcomes, these outcomes occurred in the past. None of the scenarios and contingencies that led to an outcome will ever again occur in the same way.

Waste management uncertainty results from temporal, spatial, and operational variability and the lack of knowledge [57]. Perhaps, more than most scientific venues, the factors that lead to environmental risk are highly variable, given the large number of habitats, sources of pollution, diseases in populations, geographic diversity, and many other environmental circumstances. For example, within a square meter of soil, the microbial populations, soil texture, organic matter, and chemical makeup can be highly variable. Extending this to the effect of dredging near a 10-ha wetland or trying to determine the impact of a leaking underground gasoline tank propagates these uncertainties. This is compounded by the measurement imprecision, voids and gaps in observations, practical obstacles (e.g., no access to private property and physical barriers), lack of consistency in measured and modeled

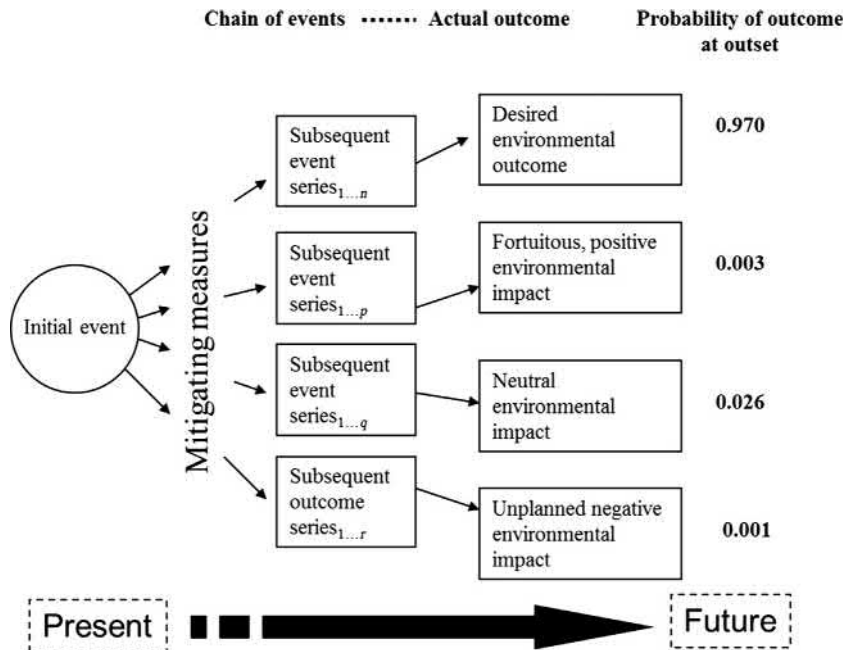


FIG. 35.11 The Event Tree, where probabilities in Fig. 25.10 increase for both desirable and adverse outcomes (fictitious data). Source: D.A. Vallero, T.M. Letcher, *Unraveling Environmental Disasters*, Newnes, 2012.

results, and simply not being able to understand what the information means, that is, structural uncertainty [58].

Environmental and health risk distinguish carcinogenic from noncancer outcomes. The term “noncancer” is commonly used to separate cancer outcomes (e.g., bladder cancer, leukemia, or adenocarcinoma of the lung) from other maladies, such as neurotoxicity, immune system disorders, and endocrine disruption. The policies of many regulatory agencies and international organizations treat cancer differently than noncancer effects, particularly in how the dose-response curves are drawn. As discussed in the dose-response curves, there is no safe dose for carcinogens. Cancer dose-response is almost always a nonthreshold curve, that is, no safe dose is expected (Curve A in Fig. 35.7). Theoretically at least, noncancer outcomes can have a dose below which the adverse outcomes do not present themselves (Curve B in Fig. 35.7).

So, for all other diseases, safe doses of compounds can be established. These are known as reference doses (RfD), usually based on the oral exposure route. If the substance is an air pollutant, the safe dose is known as the reference concentration (RfC), which is calculated in the same manner as the RfD, using units that apply to air (e.g., $\mu\text{g m}^{-3}$). These references are calculated from thresholds below which no adverse effect is observed in animal and human studies. If the models and data were perfect, the safe level would be the threshold, known as the no observed adverse effect level (NOAEL).

The term “noncancer” has a completely different meaning than the term “anticancer” or “anticarcinogens.” Anticancer procedures include radiation and drugs are those that are used to attack tumor cells. Anticarcinogens are chemical substances that work against the processes that lead to cancer, such as antioxidants

and essential substances that help the body's immune, hormonal, and other systems to prevent carcinogenesis.

Any hazard identification or dose-response research is never perfect and so the data derived from these investigations are often beset with various forms of uncertainty. Chief reasons for this uncertainty include variability among the animals and people being tested, as well as differences in response to the compound by different species (e.g., one species may have decreased adrenal gland activity, while another may show thyroid effects). Whereas, this is usually associated with chemical risk, these uncertainties can also be part of microbial data sets. For example, certain immunocompromised subpopulations may respond adversely to microbial exposures that are below thresholds for the general population.

Sometimes, studies only indicate the lowest concentration of a contaminant that causes the effect, that is, the lowest observed adverse effect level (LOAEL), but the NOAEL is unknown. If the LOAEL is used, one is less certain how close this is to a safe level where no effect is expected. Often, there is temporal incongruence, such as most of the studies taking place in a shorter timeframe than in the real world. Thus in lieu of long-term human studies, hazards and risks may have to be extrapolated from acute or subchronic studies of the same or similar agents. Likewise, routes and pathways of exposure used to administer the agent to subjects may differ from the likely real world exposures. For example, if the dose of substance in a research study is administered orally, but the pollutant is more likely to be inhaled by humans, this route-to-route extrapolation adds uncertainty. This is particularly problematic for microbial exposures, for example, inhalational anthrax (*Bacillus anthracis*) is more virulent in human populations than is gastrointestinal anthrax.

Finally, the hazard and exposure data themselves may be weak because the studies from which they have been gathered lack sufficient

quality or the precision, accuracy, completeness, and representativeness, or they may not be directly relevant to the risk assessment at hand.

The factors underlying the uncertainties are quantified as specific uncertainty factors (UFs). The uncertainties in the RfD are largely due to the differences between results found in animal testing and expected outcomes in human population. As in other bioengineering operations, a factor of safety must be added to calculations to account for UFs. So, for environmental risk analyses and assessments, the safe level is expressed in the RfD, or in air the RfC. This is the dose or concentration below which regulatory agencies do not expect a specific unacceptable outcome. Thus all the uncertainty factors adjust the actual measured levels of no effect (i.e., the threshold values, e.g., NOAELs and LOAELs) in the direction of a zero concentration. This is calculated as:

$$\text{RfD} = \frac{\text{NOAEL}}{\text{UF}_{\text{inter}} \times \text{UF}_{\text{intra}} \times \text{UF}_{\text{iother}}} \quad (35.3)$$

The first of the three types of uncertainty are those resulting from the difference in the species tested and that of *Homo sapiens* (UF_{inter}). Humans may differ from other species in their sensitivity to substances, which means their response to be exposed to the compound will differ from that of the tested species. This difference is reflected in UF_{inter} . The second uncertainty factor is due to the fact that certain human subpopulations are more sensitive to the effects of a compound than the general human population. These are known as intra-species uncertainty factors (UF_{intra}). The third type of uncertainties ($\text{UF}_{\text{iother}}$) results when the available data and science is lacking, such as when a LOAEL is used rather than a NOAEL. That is, data show a dose at which an effect is observed, but the "no effect" threshold must be extrapolated. Since the UFs are in the denominator, the greater the uncertainties, the closer the safe level (i.e., the RfD) is to zero, that is, the threshold is divided by these factors.

The UFs are usually multiples of 10, although the UF_{other} can range from 2 to 10.

A particularly sensitive subpopulation is children, since they are growing and tissue development is much more prolific than in older years. To address these sensitivities, the Food Quality Protection Act (FQPA) now includes what is known as the “ $10\times$ ” rule. This rule requires that the RfD for products regulated under FQPS, for example, pesticides, must include an additional factor of 10 of protection of infants, children, and females between the ages of 13 and 50 years old. This factor is included in the RfD denominator along with the other three UF values. The RfD that includes the UFs and the $10\times$ protection is known as the population adjusted dose (PAD). A risk estimate that is $<100\%$ of the acute or chronic PAD does not exceed the Agency’s risk concern.

An example of the use of an RfD as a factor of safety can be demonstrated by the U.S. Environmental Protection Agency’s decision making regarding the reregistration of the organophosphate pesticide, chlorpyrifos. The acute dietary scenario had a NOAEL of $0.5\text{ mg kg}^{-1}\text{ d}^{-1}$ (where d refers to day) and the three UF values equaled 100. Thus the acute RfD $= 5\times 10^{-3}\text{ mg kg}^{-1}\text{ d}^{-1}$ but the more protective acute PAD $5\times 10^{-4}\text{ mg kg}^{-1}\text{ d}^{-1}$. The chronic dietary scenario is even more protective, since the exposure is long term. The chronic NOAEL was found to be $0.03\text{ mg kg}^{-1}\text{ d}^{-1}$. Thus the chronic RfD for chlorpyrifos $= 3\times 10^{-4}\text{ mg kg}^{-1}\text{ d}^{-1}$ and the more protective acute PAD $5\times 10^{-5}\text{ mg kg}^{-1}\text{ d}^{-1}$. Therefore had the NOAEL threshold been used alone without the safety adjustment of the RfD, the allowable exposure would have been three orders of magnitude higher [17].

Uncertainty can also come from error. Two errors can occur when information is interpreted in the absence of sound science. The first is the *false negative*, or reporting that there is no problem when one in fact exists. The need to address this problem is often at the core of the positions taken

by environmental and public health agencies and advocacy groups. They ask questions like:

- What if a leachate monitor’s level of detection is above that needed to show that a contained chemical is actually being released?
- What if the leak detector registers zero, but in fact toxic substances are being released from the tank?
- Is there a way to determine the amount of waste in space quantitatively and with known levels of confidence?
- What if this substance really does cause cancer but the tests are unreliable?
- What if people are being exposed to a contaminant from a waste product, but via a pathway other than the ones being studied?
- What if there is a relationship that is different from the laboratory when this substance is released into the “real world,” such as the difference between how a chemical behaves in the human body by itself as opposed to when other chemicals are present (i.e., the problem of “complex mixtures”)?

The other concern is, conversely, the *false positive*. This can be a major challenge for public health agencies with the mandate to protect people from exposures to environmental contaminants. For example, what if previous evidence shows that an agency had listed a compound as a potential endocrine disruptor, only to find that a wealth of new information is now showing that it has no such effect? This can happen if the conclusions were based upon faulty models, or models that only work well for lower organisms, but subsequently developed models have taken into consideration the physical, chemical, and biological complexities of higher-level organisms, including humans. False positives may force public health officials to devote inordinate amounts of time and resources to deal with so-called nonproblems. False positives also erroneously

scare people about potentially useful products. False positives, especially when they occur frequently, create credibility gaps between engineers and scientists and the decision makers. In turn the public, those whom we have been charged to protect, lose confidence in us as professionals.

Environmental risk assessment calls for high quality, scientifically based information. Put in engineering language, the risk assessment process is a “critical path” in which any unacceptable error or uncertainty along the way will decrease the quality of the risk assessment and, quite likely, will lead to a bad environmental decision.

6 EXPOSURE ESTIMATION

An exposure is any contact with an agent [59]. For chemical and biological agents this contact can come about from a number of exposure pathways, that is, routes taken by a substance, beginning with its source to its end point (i.e., a target organ, like the liver, or a location short of that, such as in fat tissues).

Exposure results from sequential and parallel processes in the environment, from release to environmental partitioning to movement through pathways to uptake and fate in the organism (see Fig. 35.12). The substances often change to other chemical species as a result of the body’s metabolic and detoxification processes. Certainly, genetic modifications can affect such processes. New substances, known as degradation products or metabolites, are produced as cells use the parent compounds as food and energy sources. These metabolic processes, such as hydrolysis and oxidation, are the mechanisms by which chemicals are broken down.

Physical agents, such as electromagnetic radiation, ultraviolet (UV) light, and noise, do not follow this pathway exactly. The contact with these sources of energy can elicit a physiological

response that may generate endogenous chemical changes that behave somewhat like the metabolites. For example, UV light may infiltrate and damage skin cells. The UV light helps to promote skin tumor promotion by activating the transcription factor complex activator protein-1 (AP-1) and enhancing the expression of the gene that produces the enzyme cyclooxygenase-2 (COX2). Noise, that is, acoustical energy, can also elicit physiological responses that affect an organism’s chemical messaging systems, that is, endocrine, immune, and neural. It is possible that genetically modified organisms will respond differently to these physical agents than their unmodified counterparts.

The exposure pathway also includes the ways that humans and other organisms can come into contact with the hazard. The pathway has five parts:

1. The source of contamination (e.g., fugitive dust or leachate from a landfill)
2. An environmental medium and transport mechanism (e.g., soil with water moving through it)
3. A point of exposure (such as a well used for drinking water)
4. A route of exposure (e.g., inhalation, dietary ingestion, nondietary ingestion, dermal contact, and nasal)
5. A receptor population (those who are actually exposed or who are where there is a potential for exposure)

If all five parts are present, the exposure pathway is known as a completed exposure pathway. In addition, the exposure may be short term, intermediate, or long term. Short-term contact is known as an acute exposure, that is, occurring as a single event or for only a short period of time (up to 14 days). An intermediate exposure is one that lasts from 14 days to less than one year. Long-term or chronic exposures are greater than one year in duration.

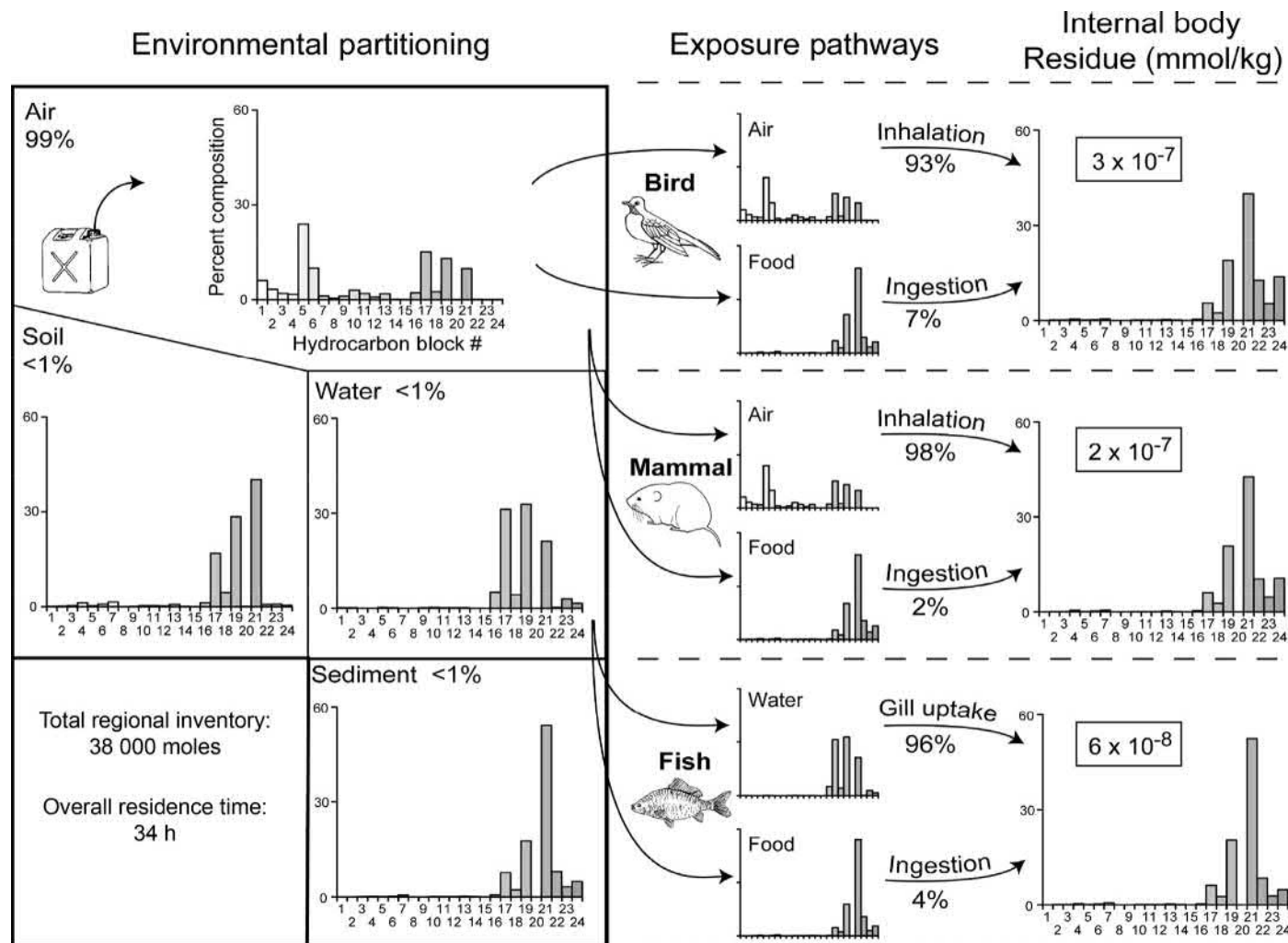


FIG. 35.12 Processes leading to organismal uptake and fate of chemical and biological agents after release into the environment. In this instance, the predominant sources are air emissions, and predominant pathway of exposure is inhalation. However, due to deposition to surface waters and the agent's affinity for sediment, the ingestion pathways are also important. Dermal pathways, in this case, do not constitute a large fraction of potential exposure. Source: T. McKone, W. Riley, R. Maddalena, R. Rosenbaum, D. Vallero, *Common issues in human and ecosystem exposure assessment: the significance of partitioning, kinetics, and uptake at biological exchange surfaces*, *Epidemiology* 17(6) (2006) S134; R.K. Rosenbaum, et al., *USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties*, *Int. J. Life Cycle Assess.* 16(8) (2011) 710–727.

Determining the exposure for a neighborhood can be complicated. For example, even if we do a good job identifying all of the contaminants of concern and its possible source (no small task), we may have little idea of the extent to which the receptor population has come into contact with these contaminants (steps 2 through 4). Thus assessing exposure involves not only the physical sciences, but the social sciences, for example, psychology and behavioral sciences. People's activities greatly affect the amount and type of exposures. That is why exposure scientists use a number of techniques to establish activity patterns, such as asking potentially exposed individuals to keep diaries, videotaping, and using telemetry to monitor vital information, for example, heart and ventilation rates.

General ambient measurements, such as air pollution monitoring equipment located throughout cities, are often not good indicators of actual population exposures. For example, metals and their compounds comprise the greatest mass of toxic substances *released* into the U.S. environment. This is largely due to the large volume and surface areas involved in metal extraction and refining operations. However, this does not necessarily mean that more people will be exposed at higher concentrations or more frequently to these compounds than to others. A substance that is released or even that if it resides in the ambient environment is not tantamount to its coming in contact with a *receptor*. Conversely, even a small amount of a substance under the right circumstances can lead to very high levels of exposure (e.g., handling raw materials and residues at a waste site).

A recent study by the Lawrence Berkley Laboratory demonstrates the importance of not simply assuming that the released or even background concentrations are a good indicator of actual exposure [19]. The researchers were interested in how sorption may affect microenvironments, so they set up a chamber constructed of

typical building materials and furnished with actual furniture like that found in most residential settings. A number of air pollutants were released into the room and monitored (see Fig. 35.13). With the chamber initially sealed, the observed decay of xylene, a volatile organic compound, in vapor phase concentrations results from adsorption onto surfaces (walls, furniture, etc.). The adsorption continues for hours, with xylene concentrations reaching a quasi-steady state. At this point the chamber was flushed with clean air to free the vapor phase xylene. The xylene concentrations shortly after the flush began to rise again until reaching a new steady state. This rise must be the result of desorption of the previously sorbed xylene, since the initial source is gone. Sorption is one of the biochemodynamic processes that must be considered to account for differences in the temporal pattern of microenvironmental (e.g., occupational) and ambient concentrations.

The simplest quantitative expression of exposure is:

$$E = D/t \quad (35.4)$$

where E is the human exposure during the time period t (units of concentration, e.g., $\text{mg kg}^{-1} \text{d}^{-1}$); D is the mass of pollutant per body mass (mg kg^{-1}); and t is time (day).

D , the chemical concentration of a pollutant, is usually measured near the interface of the person and the environment, during a specified time period. This measurement is sometimes referred to as the potential dose (i.e., the chemical has not yet crossed the boundary into the body, but is present where it may enter the person, such as on the skin, at the mouth, or at the nose).

Expressed quantitatively, exposure is a function of the concentration of the agent and time. It is an expression of the magnitude and duration of the contact. That is, exposure to a contaminant is the concentration of that contact in a medium integrated over the time of contact:

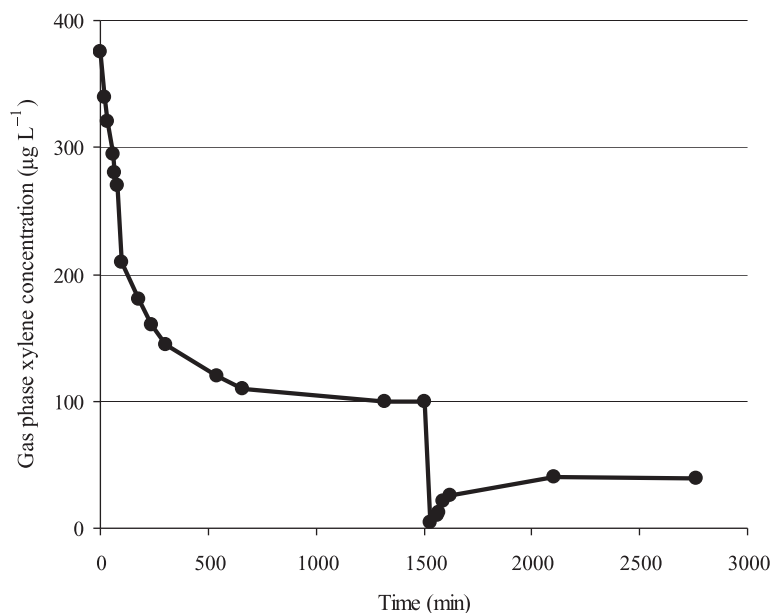


FIG. 35.13 Concentrations of xylene measured in its vapor phase in a chamber sealed during adsorption and desorption periods. Source: Adapted from: [60].

$$E = \int_{t=t_1}^{t=t_2} C(t) dt \quad (35.5)$$

where E is the exposure during the time period from t_1 to t_2 , and $C(t)$ is the concentration at the interface between the organism and the environment, at time t .

The concentration at the interface is the potential dose (i.e., the agent has not yet crossed the boundary into the body, but is present where it may enter the receptor). Since the amount of a chemical agent that penetrates from the ambient atmosphere into a control volume affects the concentration term of the exposure equation, a complete mass balance of the contaminant must be understood and accounted for; otherwise exposure estimates will be incorrect. Recall that the mass balance consists of all inputs and outputs, as well as chemical changes to the contaminant:

$$\begin{aligned} &\text{Accumulation or loss of contaminant A} \\ &= \text{Mass of A transported in} \\ &\quad - \text{Mass of A transported out} \pm \text{Reactions} \end{aligned} \quad (35.6)$$

The reactions may be either those that generate substance A (i.e., sources) or those that destroy substance A (i.e., sinks). Thus the amount of mass transported in is the inflow to the system that includes pollutant discharges, transfer from other control volumes and other media (e.g., if the control volume is soil, the water and air may contribute mass of chemical A), and formation of chemical A by abiotic chemistry and biological transformation. Conversely, the outflow is the mass transported out of the control volume, which includes uptake, by biota, transfer to other compartments (e.g., volatilization to the atmosphere) and abiotic and biological degradation of chemical A. This means the rate of change of the mass in a

control volume is equal to the rate of chemical A transported into the control volume minus the rate of chemical A transported out, plus the rate of production from sources, and minus the rate of elimination by sinks. Stated as a differential equation, the rate of change contaminant A is:

$$\frac{d[A]}{dt} = -v \cdot \frac{d[A]}{dx} + \frac{d}{dx} \left(\Gamma \cdot \frac{d[A]}{dx} \right) + r \quad (35.7)$$

where v is the fluid velocity, Γ is a rate constant specific to the environmental medium, $\frac{d[A]}{dx}$ is the concentration gradient of chemical A, and r refers to the internal sinks and sources within the control volume.

Reactive compounds can be particularly difficult to measure. For example, many volatile organic compounds in the air can be measured by first collecting in stainless steel canisters and analyzed by chromatography in the lab. However, some of these compounds, like the carbonyls (notably aldehydes like formaldehyde and acetaldehyde) are prone to react inside the

canister, meaning that by the time the sample is analyzed a portion of the carbonyls are degraded (underreported). Therefore other methods, such as trapping the compounds with dinitrophenyl hydrazine (DNPH) treated silica gel tubes that are frozen until being extracted for chromatographic analysis. The purpose of the measurement is to see what is in the air, water, soil, sediment, or biota at the time of sampling, so any reactions before the analysis give measurement error.

If the released chemical is reactive, some or all of it may have changed into another form (i.e., *speciated*) by the time it is measured. Even relatively nonreactive compounds may speciate between when the sample is collected (e.g., in a water sample, an air canister, a soil core, or a bag) and when the sample is analyzed. In fact, each contaminant has unique characteristics which vary according to the type of media in which it exists, and extrinsic conditions like temperature and pressure (see [Table 35.4](#)).

TABLE 35.4 Effect of Extrinsic Conditions on Chemicals, as Represented by Preservation and Holding Time Requirements for Anion Sampling and Analysis

Analyte	Preservation	Holding Time
PART A: Common Anions		
Bromide	None required	28 days
Chloride	None required	28 days
Fluoride	None required	28 days
Nitrate-N	Cool to 4°C	48 h
Nitrite-N	Cool to 4°C	48 h
Ortho-Phosphate-P	Cool to 4°C	48 h
Sulfate	Cool to 4°C	28 days
PART B: Inorganic Disinfection By-Products		
Bromate	50 mgL ⁻¹ EDA	28 days
Bromide	None required	28 days
Chlorate	50 mgL ⁻¹ EDA	28 days
Chlorite	50 mgL ⁻¹ EDA, cool to 4°C	14 days

Source: Method 300.1: Determination of Inorganic Anions in Drinking Water by Ion Chromatography, 1997.

The general exposure Eq. (35.7) is rewritten to address each route of exposure, accounting for chemical concentration and the activities that affect the time of contact. The exposure calculated from these equations is actually the chemical intake (*I*) in units of concentration (mass per volume or mass per mass) per time, such as $\text{mg kg}^{-1} \text{ d}^{-1}$:

$$I = \frac{C \cdot CR \cdot EF \cdot ED \cdot AF}{BW \cdot AT} \quad (35.8)$$

where *C* is the chemical concentration of contaminant (mass per volume); *CR* is the contact rate (mass per time); *EF* is the exposure frequency (number of events, dimensionless); and *ED* is the exposure duration (time).

The factors in Eq. (35.8) are further specified for each route of exposure, such as the lifetime average daily dose (LADD) as presented in Table 35.5. Exposure can be calculated for various scenarios that will change the exposure duration and

TABLE 35.5 Equations for Calculating Lifetime Average Daily Dose (LADD) for Various Routes of Exposure

Route of Exposure	Equation LADD (in $\text{mg kg}^{-1} \text{ d}^{-1}$) =	Definitions
Inhaling aerosols (particulate matter)	$\frac{(C) \cdot (PC) \cdot (IR) \cdot (RF) \cdot (EL) \cdot (AF) \cdot (ED) \cdot (10^{-6})}{(BW) \cdot (TL)}$	<i>C</i> = concentration of the contaminant on the aerosol/particle (mg kg^{-1}) <i>PC</i> = particle concentration in air (gm m^{-3}) <i>IR</i> = inhalation rate ($\text{m}^{-3} \text{ h}^{-1}$) <i>RF</i> = respirable fraction of total particulates (dimensionless, usually determined by aerodynamic diameters, for example, $2.5 \mu\text{m}$) <i>EL</i> = exposure length (h d^{-1}) <i>ED</i> = duration of exposure (d) <i>AF</i> = absorption factor (dimensionless) <i>BW</i> = body weight (kg) <i>TL</i> = typical lifetime (d). 10^{-6} is a conversion factor (kg to mg)
Inhaling vapor phase contaminants	$\frac{(C) \cdot (IR) \cdot (EL) \cdot (AF) \cdot (ED)}{(BW) \cdot (TL)}$	<i>C</i> = concentration of the contaminant in the gas phase (mg m^{-3}) Other variables the same as previously
Drinking water	$\frac{(C) \cdot (CR) \cdot (ED) \cdot (AF)}{(BW) \cdot (TL)}$	<i>C</i> = concentration of the contaminant in the drinking water (mg L^{-1}) <i>CR</i> = rate of water consumption (L d^{-1}) <i>ED</i> = duration of exposure (d) <i>AF</i> = portion (fraction) of the ingested contaminant that is physiologically absorbed (dimensionless) Other variables are the same as previously
Contact with soil-borne contaminants	$\frac{(C) \cdot (SA) \cdot (BF) \cdot (FC) \cdot (SDF) \cdot (ED) \cdot (10^{-6})}{(BW) \cdot (TL)}$	<i>C</i> = concentration of the contaminant in the soil (mg kg^{-1}) <i>SA</i> = skin surface area exposed (cm^{-2}) <i>BF</i> = bioavailability (percent of contaminant absorbed per day) <i>FC</i> = fraction of total soil from contaminated source (dimensionless) <i>SDF</i> = soil deposition, the mass of soil deposited per unit area of skin surface ($\text{mg cm}^{-1} \text{ d}^{-1}$) Other variables are the same as previously

Source: M. Derelanko, *CRC handbook of toxicology*, in: M.J. Derelanko, M.A. Hollinger (Eds.), *Risk Assessment*, CRC Press, Boca Raton, FL, 1999.

frequency. These include average daily dose (ADD), lifetime average daily dose (LADD), and acute dose rate (ADR). The averaging time (AT) differs for these exposure scenarios. The ADD averages exposure over the period of time during which the exposure occurred, making it amenable to risk calculations for many noncancer effects. The LADD is used for cancer risk assessments, with LADD usually described in terms of lifetime probabilities, although this level of exposure does not occur over the entire lifetime. Thus for LADD,

the AT is replaced with lifetime. The ADR assumes a much shorter AT, that is, one day [61].

Acute and subchronic exposures require different equations, since the exposure duration (ED) is much shorter. For example, instead of LADD, acute exposures to noncarcinogens may use maximum daily dose (MDD) to calculate exposure (see [Discussion Box 35. 1: Exposure Calculation Example](#)). However, even these exposures follow the general model given in Eq. (35.8).

DISCUSSION BOX 35. 1 EXPOSURE CALCULATION EXAMPLE

In the process of synthesizing pesticides over an 18-year period, a polymer manufacturer has contaminated the soil on its property with vinyl chloride. The plant closed 2 years ago but vinyl chloride vapors continue to reach the neighborhood surrounding the plant at an average concentration of 1 mg m^{-3} . Assume that people are breathing at a ventilation rate of $0.5 \text{ m}^3 \text{ h}^{-1}$ (about the average of adult males and females over 18 years of age [20]). The legal settlement allows neighboring residents to evacuate and sell their homes to the company. However, they may also stay. The neighbors have asked for advice on whether to stay or leave, since they have already been exposed for 20 years.

Vinyl chloride is highly volatile, so its phase distribution will be mainly in the gas phase rather than the aerosol phase. Although some of the vinyl chloride may be sorbed to particles, we will use only vapor phase LADD equation, since the particle phase is likely to be relatively small. Also, we will assume that outdoor concentrations are the exposure concentrations. This is unlikely, however, since people spend very little time outdoors compared to indoors, so this may provide an additional factor of safety. To determine how much vinyl chloride penetrates living quarters, indoor air studies would have to be conducted. For a scientist to compare exposures, indoor air measurements should be taken.

Find the appropriate equation in [Table 35.5](#) and insert values for each variable. Absorption rates are published by the EPA and the Oak Ridge National Laboratory's Risk Assessment Information System (http://risk.lsd.ornl.gov/cgi-bin/tox/TOX_select?select=nrad). Vinyl chloride is well absorbed, so for a worst case we can assume that $AF=1$. We will also assume that the person stays in the neighborhood is exposed at the average concentration 24h a day ($EL=24$), and that a person lives the remainder of entire typical lifetime exposed at the measured concentration.

Answer:

Although the ambient concentrations of vinyl chloride may have been higher when the plant was operating, the only measurements we have are those taken recently. Thus this is an area of uncertainty that must be discussed with the clients. The common default value for a lifetime is 70 years, so we can assume the longest exposure would be 70 years (25,550 days). [Table 35.6](#) gives some of the commonly used default values in exposure assessments. If the person is now 20 years of age and has already been exposed for that time, and lives the remaining 50 years exposed at 1 mg m^{-3} :

DISCUSSION BOX 35.1 EXPOSURE CALCULATION EXAMPLE (cont'd)

$$\begin{aligned} \text{LADD} &= \frac{(C) \cdot (\text{IR}) \cdot (\text{EL}) \cdot (\text{AF}) \cdot (\text{ED})}{(\text{BW}) \cdot (\text{TL})} \\ &= \frac{(1) \cdot (0.5) \cdot (24) \cdot (1) \cdot (25550)}{(70) \cdot (25550)} \\ &= 0.2 \text{ mg kg}^{-1} \text{ d}^{-1} \end{aligned}$$

If the 20 year old leaves today, the exposure duration would be for the 20 years that the person lived in the neighborhood. Thus only the ED term would change, that is, from 25,550 days to 7300 days (i.e., 20 years).

Thus the LADD falls to 2/7 of its value:

$$\text{LADD} = 0.05 \text{ mg kg}^{-1} \text{ d}^{-1}$$

TABLE 35.6 Commonly Used Human Exposure Factors

Exposure Factor	Adult Male	Adult Female	Child (3–12 years of age) [22]
Body weight (kg)	70	60	15–40
Total fluids ingested (L d ⁻¹)	2	1.4	1.0
Surface area of skin, without clothing (m ²)	1.8	1.6	0.9
Surface area of skin, wearing clothes (m ²)	0.1–0.3	0.1–0.3	0.05–0.15
Respiration/ventilation rate (L min ⁻¹) – resting	7.5	6.0	5.0
Respiration/ventilation rate (L min ⁻¹) – light activity	20	19	13
Volume of air breathed (m ³ d ⁻¹)	23	21	15
Typical lifetime (years)	70	70	NA
National upper-bound time (90th percentile) at one residence (years)	30	30	NA
National median time (50th percentile) at one residence (years)	9	9	NA

Sources: J. Moya, et al., *Exposure factors handbook: 2011 edition*, US Environmental Protection Agency, Washington, 2011; E.J. Calabrese, *ATSDR Public Health Assessment Guidance Manual*, CRC Press, 1992.

Once the hazard and exposure calculations are done, risks can be characterized quantitatively. There are two general ways that such risk characterizations are used in environmental problem solving, that is, direct risk assessments and risk-based cleanup standards.

7 DIRECT RISK CALCULATIONS

Although in its simplest form, risk is the product of the hazard and exposure, but assumptions can greatly affect risk estimates. For example, cancer risk can be defined as the theoretical probability of contracting cancer when continually

exposed for a lifetime (e.g., 70 years) to a given concentration of a substance (carcinogen). The probability is usually calculated as an upper confidence limit. The maximum estimated risk may be presented as the number of chances in a million of contracting cancer.

Two measures of risk are commonly reported. One is the individual risk, that is, the probability of a person developing an adverse effect (e.g., cancer) due to the exposure. This is often reported as a “residual” or increased probability above background. For example, if we want to characterize the contribution of all the power plants in the United States to increased cancer incidence, the risk above background would be reported. The second way that risk is reported is population risk, that is, the annual excess number of cancers in an exposed population. The maximum individual risk might be calculated from exposure estimates based upon a

“maximum exposed individual” or MEI. The hypothetical MEI lives an entire lifetime outdoors at the point where pollutant concentrations are highest. Assumptions about exposure will greatly affect the risk estimates. For example, the cancer risk from power plants in the United States has been estimated to be that the risk to be 100- to 1000-fold lower for an average exposed individual than that calculated for the MEI.

For cancer risk assessments, the hazard is generally assumed to be the slope factor and the long-term exposure is the lifetime average daily dose:

$$\text{Cancer risk} = \text{SF} \times \text{LADD} \quad (35.9)$$

Therefore cancer risk can be calculated if the exposure (e.g., LADD) and potency (e.g., the cancer slope factor) are known (see [Discussion Box 35.2: Cancer Risk Calculation Example](#)).

DISCUSSION BOX 35.2 CANCER RISK CALCULATION EXAMPLE

Using the lifetime average daily dose value from the vinyl chloride exposure calculation in the previous section, estimate the direct risk to the people living near the abandoned polymer plant. What information needs to be communicated?

Insert the calculated LADD values and the vinyl chloride inhalation slope factor of 3.00×10^{-1} from Appendix 2. The two LADD values under consideration, the cancer risk to the neighborhood exposed for an entire lifetime (exposure duration = 70 years) gives us $0.2 \text{ mg kg}^{-1} \text{ d}^{-1} \times 0.3 (\text{mg kg}^{-1} \text{ d}^{-1})^{-1} = 0.06$. This is an incredibly high risk! The threshold for concern is often 1 in a million (0.000001), while this is a probability of 6%.

Even at the shorter duration period (20 years of exposure instead of 70 years), the risk is calculated as $0.05 \times 0.3 = 0.017$ or nearly a 2% risk. The combination of a very steep slope factor and very high lifetime exposures leads to a very

high risk. Vinyl chloride is a liver carcinogen, so unless corrective actions significantly lower the ambient concentrations of vinyl chloride the prudent course of action is that the neighbors accept the buyout and leave the area.

Incidentally, vinyl chloride has relatively high water solubility and can be absorbed to soil particles, so ingestion of drinking water (e.g., people on private wells drawing water from groundwater that has been contaminated) and dermal exposures (e.g., children playing in the soil) are also conceivable. The total risk from a single contaminant like vinyl chloride is equal to the sum of risks from all pathways (e.g., vinyl chloride in the air, water and soil):

$$\text{Total risk} = \sum \text{Risks from all exposure pathways} \quad (35.10)$$

Requirements and measures of success are seldom if ever as straightforward as the vinyl chloride example. In fact, the bioengineer would be ethically remiss if the only advice given is to the local community, that is, whether or not to accept the buyout. Of course, one of the engineering canons is to serve a “faithful agent” to the clientele. However, the first engineering canon is to hold paramount the health and safety of the public. Thus the engineer must balance any proprietary information that the client wants to be protected with the need to protect public health. In this case, the engineer must inform the client and prime contractors, for example, that the regulatory agencies need to know that even if the current neighbors are moving, the threat to others, including future populations, are threatened. In other words, a systematic approach is needed, since the current population may be moved from harms way, remediation is still likely needed to reduce the vinyl chloride concentrations to acceptable levels. This is because biodynamical processes are complex. The contaminant may remain in untreated or poorly treated areas, which may later be released (e.g., future excavation, long-term transport from groundwater to surface or from groundwater to drinking water sources). Thus postclosure monitoring should be designed and operated based on worst-case scenarios.

The risk of adverse outcome other than cancer (so-called noncancer risk) is generally called the “hazard quotient” (HQ). It is calculated by dividing the maximum daily dose (MDD) by the acceptable daily intake (ADI):

$$\text{Noncancer risk} = \text{HQ} = \frac{\text{MDD}}{\text{ADI}} = \frac{\text{Exposure}}{\text{RfD}} \quad (35.11)$$

Note that this is an index, not a probability, so it is really an indication of relative risk. If the noncancer risk is >1 , the potential risk may be significant, and if the noncancer risk is <1 , the noncancer risk may be considered to be insignificant (see [Discussion Box 35.3: Noncancer Risk Calculation Example](#)). Thus the reference dose, RfD, is one type of ADI.

If a population is exposed to more than one contaminant, the hazard index (HI) can be used to express the level of cumulative noncancer risk from pollutants 1 through n :

$$\text{HI} = \sum_{i=1}^n \text{HQ} \quad (35.12)$$

The HI is useful in comparing risks at various locations, for example, benzene risks in St. Louis, Cleveland, and Los Angeles. It can also give the cumulative (additive risk) in a single population exposed to more than one

DISCUSSION BOX 35.3 NONCANCER RISK CALCULATION EXAMPLE

The chromic acid (Cr^{6+}) mists dermal chronic RfD of $6.00 \times 10^{-3} \text{ mg kg}^{-1} \text{ d}^{-1}$. If the actual dermal exposure of people living near a metal processing plant is calculated (e.g., by intake or LADD) to be $4.00 \times 10^{-3} \text{ mg kg}^{-1} \text{ day}^{-1}$, calculate the hazard quotient for the noncancer risk of the chromic acid mist to the neighborhood near the plant and interpret the meanings.

From Eq. (35.11), $\frac{\text{Exposure}}{\text{RfD}} = \frac{4.00 \times 10^{-3}}{6.00 \times 10^{-3}} = 0.67$. Since this is <1 , one would not expect people chronically exposed at this level to show adverse effects from skin contact. However, at this same chronic exposure, that is, $4.00 \times 10^{-3} \text{ mg kg}^{-1} \text{ d}^{-1}$, to hexavalent chromic acid mists via oral route, the RfD is $3.00 \times 10^{-3} \text{ mg kg}^{-1} \text{ d}^{-1}$, meaning the $\text{HQ} = 4/3$ or 1.3. The value is >1 , so we cannot rule out adverse noncancer effects.

contaminant. For example, if the HQ for benzene is 0.2 (not significant), toluene is 0.5 (not significant), and tetrachloromethane is 0.4 (not significant), the cumulative risk of the three contaminants is 1.1 (potentially significant).

Realistic estimates of the hazard and the exposures are desirable in such calculations. However, precaution is the watchword for risk. Estimations of both hazard (toxicity) and exposure are often worst-case scenarios, because the risk calculations can have large uncertainties. Models usually assume effects to occur even at very low doses. Human data are usually gathered from epidemiological studies that, no matter how well they are designed, are fraught with error and variability (science must be balanced with the rights and respect of subjects, populations change, activities may be missed, and confounding variables are ever present). Uncertainties exist in every phase of risk assessment, from the quality of data, to limitations and assumptions in models, to natural variability in environments and populations.

8 RISK-BASED CLEANUP STANDARDS

For most of the second half of the 20th century, environmental protection was based on two types of controls, that is, technology based and quality based. Technology-based controls are set according to what is “achievable” from the current state of the science and engineering. These are feasibility-based standards. The Clean Air Act has called for best achievable control technologies (BACT), and more recently for maximally achievable control technologies (MACT). Both standards reflect the reality that even though from an air quality standpoint it would be best to have extremely low levels of pollutants, technologies are not available or are not sufficiently reliable to reach these levels. Requiring unproven or unreliable technologies can even exacerbate the pollution, such as in

the early days of wet scrubbers on coal-fired power plants. Theoretically, the removal of sulfur dioxide could be accomplished by venting the power plant flue through a slurry of carbonate, but the technology at the time unproven and unreliable, allowing all-too-frequent releases of untreated emissions while the slurry systems were being repaired. Selecting a new technology over older proven techniques is unwise if the trade-off of the benefit of improved treatment over older methods is outweighed by the numerous failures (i.e., no treatment).

Technology-based standards are a part of most environmental programs. Wastewater treatment, groundwater remediation, soil cleaning, sediment reclamation, drinking water supply, air emission controls, and hazardous waste site cleanup all are in part determined by availability and feasibility of control technologies.

Quality-based controls are those that are required to ensure that an environmental resource is in good enough condition to support a particular use. For example, a stream may need to be improved so that people can swim in it and so that it can be a source of water supply. Certain streams may need higher levels of protection than others, such as the so-called wild and scenic rivers. The parameters will vary, but usually include minimum levels of dissolved oxygen and maximum levels of contaminants. The same goes for air quality, where ambient air quality must be achieved, so that concentrations of contaminants listed as National Ambient Air Quality Standards, as well as certain toxic pollutants, are below levels established to protect health and welfare.

Risk-based approaches to environmental protection, especially contaminant target concentrations, are designed to require engineering controls and preventive measures to ensure that risks are not exceeded. The risk-based approach actually embodies elements of both technology- and quality-based standards. The technology assessment helps determine how realistic it will be to meet certain contaminant concentrations,

while the quality of the environment sets the goals and means to achieve cleanup. Engineers are often asked, “How clean is clean?” When do we know that we have done a sufficient job of cleaning up a spill or hazardous waste site? It is often not possible to have nondetectable concentrations of a pollutant. Commonly, the threshold for cancer risk to a population is 1 in a million excess cancers. However, one may find that the contaminant is so difficult to remove, that we almost give up on dealing with the contamination and put in measures to prevent exposures, that is, fencing the area in and prohibiting no access. This is often done as a first step in remediation, but is an unsatisfying and controversial (and usually politically and legally unacceptable). Thus even if costs are high and technology unreliable, the engineer must find suitable and creative ways to clean up the mess and meet risk-based standards.

Risk-based target concentrations can be calculated by solving for the target contaminant concentration in the exposure and risk equations. Since risk is the hazard (e.g., slope factor) times the exposure (e.g., LADD), a cancer risk-based cleanup standard can be found by enumerating the exposure equations within the risk equation (in this instance, the drinking water equation from [Table 35.4](#)) gives:

$$\text{Risk} = \frac{C \cdot CR \cdot EF \cdot ED \cdot AF \cdot SF}{BW \cdot AT} \quad (35.13)$$

and solving for C:

$$C = \frac{\text{Risk} \cdot BW \cdot AT}{CR \cdot EF \cdot ED \cdot AF \cdot SF} \quad (35.14)$$

This is the target concentration for each contaminant needed to protect the population from the specified risk, for example, 10^{-6} . In other words, this is the concentration that must not be exceeded in order to protect a population having an average body weight and over a specified averaging time from an exposure of certain duration and frequency that leads to a risk of 1

in a million. While one-in-a-million added risk is commonly used benchmark, cleanup may not always be required to achieve this level. For example, if a site is considered to be a “removal” action, that is, the principal objective is to get rid of a sufficient amount of contaminated soil to reduced possible exposures, that risk reduction target may be as high as one additional cancer per 10,000 (i.e., 10^{-4}).

The decision regarding the actual cleanup level, including whether to approach a contaminated site or facility as a removal or a remedial action is not risk assessment, but fall within the province of risk management. The waste manager will have input to the decision, but will not be the only party in that decision. The risk assessment data and information will comprise much of the scientific underpinning of the decision, but legal, economic, and other societal drivers will also be considered to arrive at cleanup levels. It is not unusual, for example, for a legal document, such as a consent decree, to prescribe cleanup levels more protective than typical removal or remedial concentration levels ([Discussion Box 35.4](#)).

Some general risk assessment principles have been almost universally adopted by regulatory agencies, especially those concerned with cancer risks from environmental exposures (See [Table 35.7](#)).

As mentioned, many risks are not directly tied to a single agent, but occur in the milieu of mixtures and coexposures. In addition, the risks to public health, such as cancer and non-cancer endpoints, are only one class of outcomes of concern. Others include ecosystem changes from gene flow and other ecological endpoints and opportunity risks. The latter risks include those posed by not allowing biological pesticides that may be safer than abiotically derived pesticides.

A waste decision must be comprehensive. Even when one aspect seems to be very favorable for a particular site, the overall risk of one waste operation may be greater than that of

DISCUSSION BOX 35.4 RISK-BASED CONTAMINANT CLEANUP EXAMPLE

A well is the principal water supply for the town of Apple Chill. A study has found that the well contains 80 mg L^{-1} tetrachloromethane (CCl_4). Assuming that the average adult in the town drinks 2 L d^{-1} of water from the well and lives in the town for an entire lifetime, what is the lifetime cancer risk to the population if no treatment is added? What concentration is needed to ensure that the population cancer risk is below 10^{-6} ?

The lifetime cancer risk added to Apple Chill's population can be estimated using the LADD and slope factor for CCl_4 . In addition to the assumptions given, we will use default values from Table 35.5. We will also assume that people live in the town for their entire lifetimes, and that their exposure duration is equal to their typical lifetime.

Thus ED and TL terms cancel, leaving the abbreviated $\text{LADD} = \frac{(C) \cdot (\text{CR}) \cdot (\text{AF})}{(\text{BW})}$.

Since we have not specified male or female adults, we will use the average body weight, assuming that there are about the same number of males as females. We look up the absorption factor for CCl_4 and find that it is 0.85, so the adult lifetime exposure is:

$$\text{LADD} = \frac{(80) \cdot (2) \cdot (0.85)}{(65)} = 4.2 \text{ mg kg}^{-1} \text{ d}^{-1}$$

Using the midpoint value between the default values ($\frac{15+40}{2}$) = 27.5 kg for body weight and default CR values (1 L d^{-1}) the children lifetime exposure is:

$\text{LADD} = \frac{(80) \cdot (1) \cdot (0.85)}{(27.5)} = 2.5 \text{ mg kg}^{-1} \text{ d}^{-1}$ for the first 13 years, and the adult exposure of $4.2 \text{ mg kg}^{-1} \text{ d}^{-1}$ thereafter.

The oral SF for CCl_4 is $1.30 \times 10^{-1} \text{ kg d}^{-1}$, so the added adult lifetime risk from drinking the water is:

$$4.2 \times (1.30 \times 10^{-1}) = 5.5 \times 10^{-1}$$

And, the added risk to children is:

$$2.5 \times (1.30 \times 10^{-1}) = 3.3 \times 10^{-1}.$$

Some subpopulations are more vulnerable to exposures than others. For example, for children, environmental and public health agencies recommend an additional factor of safety beyond what would be used to calculate risks for adults. This is known as the "10×" rule, that is, children need to be protected 10 times more than adults because they have longer life expectancies (so latency periods for cancer need to be accounted for), and their tissue is developing prolifically and changing. So, in this case, with the added risk, our reported "risk" would be 3.3. While this is statistically impossible (i.e., one cannot have a probability greater than one because it would mean that the outcome is >100% likely, which of course is impossible!), it is actually an adjustment to the cleanup concentration. Since the combination of a very high slope of the dose-response curve and a very high LADD increases the risk, children need a measure of protection beyond the general population. This is accomplished either by removing the contaminants from the water or the provision of a new water supply. In any event, the city public works and/or health department should mandate another source of drinking water (e.g., bottled water) immediately.

The cleanup of the water supply to achieve risks below 1 in a million can be calculated from the same information and reordering the risk equation to solve for C:

$$\text{Risk} = \text{LADD} \times \text{SF}$$

$$\text{Risk} = \frac{(C) \cdot (\text{CR}) \cdot (\text{AF}) \cdot (\text{SF})}{(\text{BW})}$$

$$C = \frac{(\text{BW}) \cdot \text{Risk}}{(\text{CR}) \cdot (\text{AF}) \cdot (\text{SF})}$$

Based on adult LADD, the well water must be treated so that the tetrachloromethane concentrations are below:

DISCUSSION BOX 35.4 RISK-BASED CONTAMINANT CLEANUP EXAMPLE *(cont'd)*

$$C = \frac{(65) \cdot 10^{-6}}{(2) \cdot (0.85) \cdot (0.13)} = 2.9 \times 10^{-4} \text{ mgL}^{-1} \\ = 290 \text{ ngL}^{-1}$$

Based on children's LADD, and the additional "10×," the well water must be treated so that the tetrachloromethane concentrations are below:

$$C = \frac{(27.5) \cdot 10^{-7}}{(1) \cdot (0.85) \cdot (0.13)} = 2.5 \times 10^{-5} \text{ mgL}^{-1} \\ = 25 \text{ ngL}^{-1}$$

The town must remove the contaminant so that the concentration of CCl_4 in the finished water will be at a level six orders of magnitude less than the untreated well water, that is, lowered from 80 mgL^{-1} to 25 ngL^{-1} . Cleanup standards are part of the arsenal needed to manage risks. However, other considerations need to be given to a contaminated site, such as how to monitor the progress in lowering levels and how to ensure

that the community stays engaged and is participating in the cleanup actions, where appropriate. Even when the engineering solutions are working well, the waste manager must allot sufficient time and effort to these other activities, otherwise skepticism and distrust can arise.

It is important to note that these example calculations are instructive, but not sufficient. There are numerous, often better ways to calculate risk-based cleanup concentrations. As mentioned, assuming lifetime exposure durations is a conservative estimation of long-term exposures, especially for chronic diseases, for example, cancer and cardiovascular ailments. Regarding toxicity, the literature is constantly advancing for both cancer and non-cancer endpoints, with slope factors and RfDs updated. Every cleanup is unique, so there will also likely be additional requirements beyond exposure and hazard factors in the risk equation.

TABLE 35.7 General Principles Applied to Health and Environmental Risk Assessments Conducted by Regulatory Agencies in the United States

Principle	Explanation
Human data are preferable to animal data.	For purposes of hazard identification and dose-response evaluation, epidemiological and other human data better predict health effects than animal models
Animal data can be used in lieu of sufficient, meaningful human data	While epidemiological data are preferred, agencies are allowed to extrapolate hazards and to generate dose-response curves from animal models
Animal studies can be used as basis for risk assessment	Risk assessments can be based upon data from the most highly sensitive animal studies
Route of exposure in animal study should be analogous to human routes	Animal studies are best if from the same route of exposure as those in humans, for example, inhalation, dermal, or ingestion routes. For example, if an air pollutant is being studied in rats, inhalation is a better indicator of effect than if the rats are dosed on the skin or if the exposure is dietary

Continued

TABLE 35.7 General Principles Applied to Health and Environmental Risk Assessments Conducted by Regulatory Agencies in the United States—cont'd

Principle	Explanation
Threshold is assumed for noncarcinogens	For noncancer effects, for example, neurotoxicity, endocrine dysfunction, and immunosuppression, there is assumed to be a safe level under which no effect would occur (e.g., “no observed adverse effect level,” NOAEL, which is preferred, but also “lowest observed adverse effect level,” LOAEL)
Threshold is calculated as a reference dose or reference concentration (air)	Reference dose (RfD) or concentration (RfC) is the quotient of the threshold (NOAEL) divided by factors of safety (uncertainty factors and modifying factors; each usually multiples of 10): $\text{RfD} = \frac{\text{NOAEL}}{\text{UF} \times \text{MF}}$
Sources of uncertainty must be identified	Uncertainty factors (UFs) address: • Interindividual variability in testing • Interspecies extrapolation • LOAEL-to-NOAEL extrapolation • Subchronic-to-chronic extrapolation • Route-to-route extrapolation • Data quality (precision, accuracy, completeness, and representativeness) Modifying factors (MFs) address uncertainties that are less explicit than the UFs
Factors of safety can be generalized.	The uncertainty and modifying factors should follow certain protocols, e.g., 10=for extrapolation from a sensitive individual to a population; 10=rat-to-human extrapolation, 10=subchronic-to-chronic data extrapolation and 10=LOAEL used instead of NOAEL.
No threshold is assumed for carcinogens	There is no safe level of exposure is assumed for cancer-causing agents
Precautionary principle applied to cancer model	A linear, no-threshold dose-response model is used to estimate cancer effects at low doses, that is, to draw the unknown part of the dose-response curve from the region of observation (where data are available) to the region of extrapolation
Precautionary principle applied to cancer exposure assessment	The most highly exposed individual is generally used in the risk assessment (upper-bound exposure assumptions). Agencies are reconsidering this worst-case policy and considering more realistic exposure scenarios

Source: EPA/600/R-03/036, *General Principles for Performing Aggregate Exposure and Risk Assessment*, 2001.

another (e.g., less reliance of toxic raw materials, decreased likelihood of release of chemical toxins). Thus a complete life cycle must be constructed and the composite and individual risks compared among various alternatives.

One of the most difficult risks to quantify is the opportunity risk. For example, how can the loss of the opportunity that a biotechnology affords be compared to the risk it poses? For example, if regulatory agencies

are overly cautious about approving a cancer drug that may entail the introduction of carcinogens from possible environmental releases, the risk assessment may indicate that the overall cancer risk is actually improved if the cancers that are prevented and treated with the new drug are part of the risk calculation. Usually, however, it is not that straightforward. For example, what if the cancer risk that is being treated by

the drug is relatively benign (e.g., basal cell skin cancer) compared to the more virulent form from the pollutants introduced from the bioreactor (e.g., pancreatic cancer)? Or, what if the outcomes are ecological versus public health? The risk decision and management process must consider these trade-offs.

8.1 Causality

Just from the arithmetic, it should be noted that zero risk can be calculated when either the hazard (e.g., toxicity) does not exist or when the exposure to that hazard is zero. A substance found to be associated with cancers based upon animal testing or observations of human populations can be further characterized. As discussed in [Chapter 33](#), linking causes to outcomes begins with the weight of evidence and statistical association. The association of two factors, such as the level of exposure to a compound and the occurrence of a disease, does not necessarily mean that one necessarily “causes” the other. Often, after study, a third variable explains the relationship. However, it is important for science to do what it can to link causes with effects. Otherwise, corrective and preventive actions cannot be identified. So, strength of association is a beginning step toward cause and effect. A major consideration in strength of association is the application of sound technical judgment of the weight of evidence. For example, characterizing the weight of evidence for carcinogenicity in humans consists of three major steps [\[23\]](#):

1. Characterization of the evidence from human studies and from animal studies individually;
2. Combination of the characterizations of these two types of data to show the overall weight of evidence for human carcinogenicity; and,
3. Evaluation of all supporting information to determine if the overall weight of evidence should be changed.

Note that none of these steps is absolutely certain.

Bioengineers need tools to support the risk analysis, but none or all of these tools provide a surefire answer to biotechnological risks. They are too complicated and complex for simple risk calculations. Certainly, components of biotechnologies can indeed be evaluated for their human and ecosystem risks. For example, many of the solvents and other chemicals used in the purification and other steps in bioreactors have been studied sufficiently so that they have well-defined dose-response curves and other hazard metrics.

There are numerous ways to evaluate the performance of a waste system. Does it “work” (effectiveness)? Is it the best way to reach the end for which we strive (efficiency)? If it works and if it is the best means of providing the outcome, what is the probability of benefit from the system for a societal (medical, industrial, agricultural, or environmental) problem under prescribed conditions. For example, the efficacy of a medical technology is often assessed using case-control studies, wherein controlled trials of an experimental therapy are compared to a control (e.g., case = biotechnology; control = placebo) [\[26\]](#).

Engineers add a few steps. We must consider whether or not the technology will likely continue to “work as desired” (reliability) and, further, we must consider the hazards that can come about as the new technology is used. Risk is a function of likelihood that the hazard will in fact be encountered, so we must also try to predict the adverse implications that society might face (risk). Thus the “risk” refers to the possibility and likelihood of undesirable and possibly harmful effects. Errors in risk prediction can range from not foreseeing outcomes that are merely annoying (e.g., occasional odors) to those that are devastating (e.g., the release of carcinogens into the environment) [\[27\]](#).

A classic example of a failure due to poor accountability, albeit not related to waste management, was the decision making related to Ford Pinto, a subcompact car produced by Ford Motor Company between 1971 and 1980. The

car's fuel tank was poorly placed in such a way that increased the probability of a fire from fuel spillage by a rear collision. A confluence of events, including the poor design, the likelihood of rear-end crashes, and lack of public knowledge of the risk, resulted in injuries and fatalities. The ensuing adverse implications manifested in the series of injuries that resulted from the defect could have been predicted at some level of accuracy. Perhaps, they were, and dismissed or overrun by opposing viewpoints in the boardroom. If so, this is an example of detrimental single-mindedness. Financial considerations appear to have trumped safety and health. Often, the problem is not a question of right versus wrong, but of one right versus another right. Certainly, financial feasibility is important (the next chapter is dedicated to it), but the public's safety, health, or welfare always has primacy.

Waste managers must often rely in part on semiquantitative or qualitative risk assessments. Retrospective failure analyses can be more quantitative, since there are forensic techniques available to tease out and assign weights to the factors that led to the outcome. There are even methods to calculate outcomes had other steps been taken.

9 RELIABILITY

Reliability, like risk, is an expression that incorporates probability, but instead of conveying something bad, it expresses the likelihood of a good, or at least *desired*, outcome. Reliability is the extent to which something can be trusted. A system, process, or item is reliable so long as it performs the designed function under the specified conditions during a certain period. Thus reliability is a metric of accountability for waste management, that is, reliability means that the systems selected and managed will not fail during their proposed operating periods. Or, stated more positively, reliability is the

mathematical expression of success. Reliability is the probability that something that is in operation at time 0 (t_0) will still be operating until the designed life (time $t = (t_i)$). As such, it is also a measure of the engineer's social accountability. Neighborhoods, municipalities, and other clients want to be assured that the bioremediation project will work as designed and will not fail to treat the toxic waste.

The probability of a failure per unit time is the "hazard" rate, but many engineers may recognize it as a "failure density," or $f(t)$. This is a function of the likelihood that an adverse outcome will occur, but note that it is not a function of the severity of the outcome. The $f(t)$ is not affected by whether the outcome is very severe (such as pancreatic cancer and loss of an entire species) or relatively benign (muscle soreness or minor leaf damage). The likelihood that something will fail at a given time interval can be found by integrating the hazard rate over a defined time interval:

$$P\{t_1 \leq T_f \leq t_2\} = \int_{t_1}^{t_2} f(t)dt \quad (35.15)$$

where T_f = time of failure.

Thus the reliability function $R(t)$, of a system at time t is the cumulative probability that the system has not failed in the time interval from t_0 to t_i :

$$R(t) = P\{t_1 \leq T_f \leq t_1\} = 1 - \int_0^t f(x)dx \quad (35.16)$$

Engineers must be humble, since everything designed by humans *will* fail. It is simply a question of when. All that an engineer or waste manager can do is extend the optimal time, that is, increasing t_i to making the system more resilient under conditions that would otherwise lead to failure. For example, proper engineering design of a leachate collection system should work well, not only during "normal" conditions, but resist failure during hostile conditions, for example, storm and seismic events. A design flaw occurs

if the wrong material is used, for example, not matched to the soils and hydrology of the landfill area. However, even when the proper materials are used, the failure is not eliminated entirely. In our case, leakage occurs, but at a slower rate for lesser toxic compounds (e.g., a few mg per year) to 100% containment for years for less toxic compounds, decades for recalcitrant organics, and thousands of years for radioactive materials would still be reached eventually. Selecting the right materials simply protracts the time before the failure occurs (increases T_f) [54].

9.1 Resilience

Reliable systems are also generally resilient systems. The two types of resilience discussed in the book, that is, ecosystem resilience (see [Chapter 8](#)) and engineering resilience, are mirror images of one another. The less resilient is a system, the more that the engineer and waste manager must do to make it reliable. A very resilient natural system can withstand a wide array of insult. A system that lacks resilience is a sensitive and vulnerable system, needing controls to remain operational when conditions change.

Resilient systems have wide tolerances, whereas sensitive system is easily harmed outside of very narrow tolerance ranges. Thus an ecologically resilient system is in less need of engineering controls against insult than a nonresilient system. For example, releasing an amount of a nutrient to a resilient system that causes little impact could be devastating to a nonresilient system.

Unfortunately, human activities can transform resilient systems into nonresilient ones. For example, a wild, biodiverse area may be quite resilient in the face of drought and insect infestation. However, building roads and infrastructure around and near this area could reduce biodiversity and change biological processes, making it less able to withstand these insults. Thus the waste manager should

consider how otherwise desirable projects may affect system resilience. One consequence could be that a previously unmanaged or passively managed area would become one that must be actively managed, for example, watering, fertilizing, and protecting from pests. This should be factored into alternative comparisons (see [Chapter 36](#)).

9.2 Margins of Safety

The reliability of a system must be matched to an adequate margin of safety. So, if the municipal solid waste landfill leaks after 100 years, few reasonable people would complain. If it fails after 10 years, when stakeholders had been assured 100% containment for 5 years, there may still be complaints, so long as the acceptable failure rate and margin of safety had been fully disclosed. If it fails after 10 years, but its specifications require 20 years, this may very well constitute an unacceptable risk. Obviously, other factors must be considered, such as sensitive subpopulations. For example, it may be found that the fugitive dust from the landfill does little harm to the general population, but in certain subgroups (e.g., asthmatic children) the reliability is not acceptable. The engineer and waste manager must fully disclose such limitations.

Reliability engineering, a discipline within engineering, considers the expected or actual reliability of a process, system, or piece of equipment to identify the actions needed to reduce failures, and once a failure occurs, how to manage the expected effects from that failure. Thus reliability is the mirror image of failure. Since risk is really the probability of failure (i.e., the probability that our system, process, or equipment will fail), risk and reliability are two sides of the same coin. The most common graphical representation of engineering reliability is the so-called bathtub curve (Fig. 33.3 in [Chapter 33](#)). The landfill, incinerator, or other waste system must have a long steady state, useful life compared to the regions of higher failure rates.

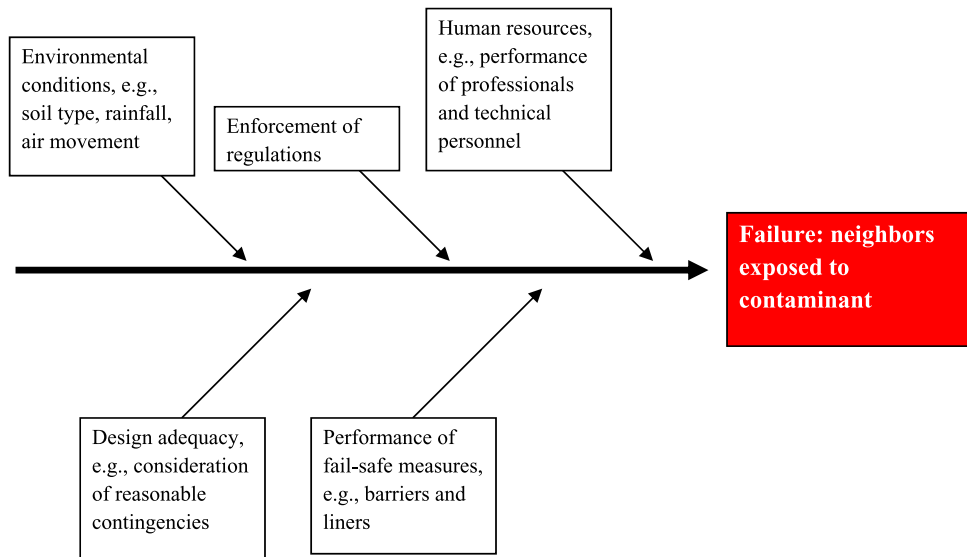


FIG. 35.14 Fishbone reliability diagram showing contributing causes to an adverse outcome (exposure to an environmental contaminant). Adapted from D.A. Vallero, P.A. Vesilind, *Socially Responsible Engineering: Justice in Risk Management*, Wiley Online Library, 2007.

Another way to visualize reliability as it pertains to biotechnology is to link potential causes to effects. Cause and effect diagrams (also known as *Ishikawa diagrams*) identify and characterize the totality of causes or events that contribute to a specified outcome event. The “fishbone” diagram (see Fig. 35.14) arranges the categories of all causative factors according to their importance (i.e., their share of the cause). The construction of this diagram begins with the failure event to the far right (i.e., the “head” of the fish), followed by the spine (flow of events leading to the failure). The “bones” are each of the contributing categories. This can be a very effective tool in explaining failures to clients and the public. Even better, the engineer may construct the diagrams in “real time” at a design meeting. This will help to open the design for peer review and will help get insights, good and bad, early in the design process [62].

The premise behind cause and effect diagrams like the fishbones and other failure logic

is that all the causes must connect through a logic gate. This is not always the case, so another more qualitative tool may need to be used, such as the Bayesian belief network (BBN). Like the fishbone, the BBN starts with the failure (see Fig. 35.15). Next, the most immediate contributing causes are linked to the failure event. The next group of factors that led to the immediate causes are then identified, followed by the remaining contributing groups. This diagram helps to identify and weight the contributing factors, allowing for investigations of how one group of factors impacts the others.

As was the case for risk, the engineering and scientific communities may define reliability in nuanced ways. Environmental engineering and other empirical sciences also use the term “reliability,” to indicate quality, especially for data derived from measurements, including health data. In this use, reliability is defined as the degree to which measured results are dependable and consistent with respect to the study objectives, for example, stream water

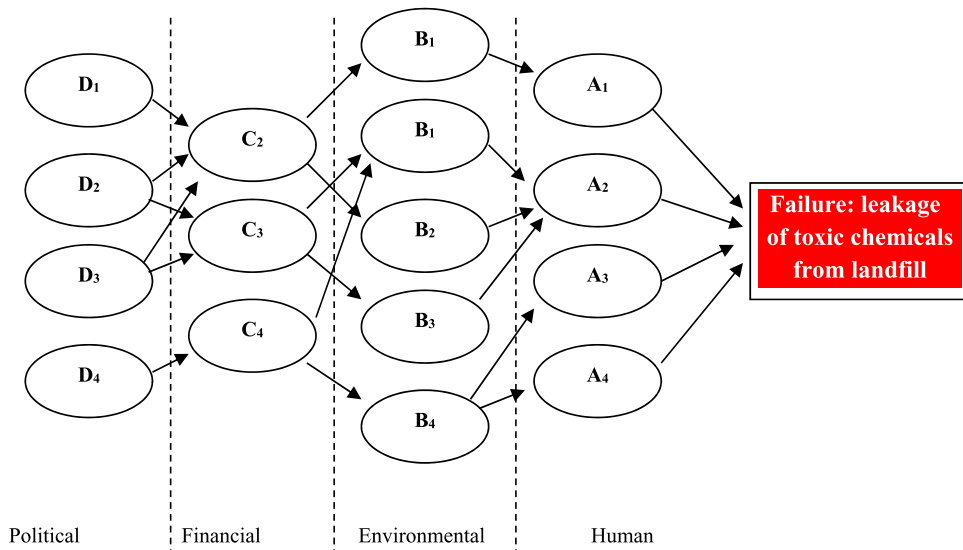


FIG. 35.15 Bayesian belief network, with three groups of contributing causes leading to a failure. Adapted from D.A. Vallero, P.A. Vesilind, *Socially Responsible Engineering: Justice in Risk Management*, Wiley Online Library, 2007.

quality. This specific connotation is sometimes called “test reliability” in that it indicates how consistent measured values are over time, how these values compare to other measured values, and how they differ when other tests are applied. Test reliability, like engineering reliability, is a matter of trust. As such, it is often paired with test validity, that is, just how near to the true value (as indicated by some type of known standard) the measured value is. The less reliable and valid the results, the less confidence scientists and engineers have in interpreting and using them. This is very important in engineering communications generally and risk communications specifically.

10 CONCLUSIONS

Waste management success is a function of the amount of risk that has been reduced or avoided. Decisions must be based on scientifically credible information. This information is part of the risk assessment that informs waste

management decisions. Thus the success of all waste operations is, to some extent, a reflection of the operation’s hazards and potential exposures to these hazards. Thus the waste manager is accountable for reducing risks, which means that the systems to do so are reliable.

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Evaluating the Feasibility of Public Projects

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OUTLINE

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1 INTRODUCTION

The previous chapters introduced several approaches for determining whether a project is acceptable. This aspect of acceptability is based on the risks that may result, the reliability in the design and operation of the project, its resilience to external stress, the ease with which the project can be operationalized and managed by governance, and the means of communicating with various stakeholders.

Certainly, these are crucial criteria that must be underpinned with sound science and engineering. Another aspect of acceptability is that

the project must also be cost effective and feasible. Privately funded and managed projects share many feasibility aspects with public projects. Indeed, many of the contracted and private concerns have public interests and visibility, including waste collection, hazardous materials handling, treatment, engineering, and remediation. However, the ultimate responsibility for waste management rests with public agencies.

This chapter draws upon engineering economics to introduce approaches for evaluating the acceptability of proposed, new projects and upgrades and enhancements to existing projects.

2 ENGINEERING ECONOMICS

Engineering economics is used to determine whether a project is worthwhile, to prioritize various projects that may serve the same purpose or function, and to assign value or importance to design specifications. For example, engineering economics may help the waste manager determine whether to invest in new trucks or keep repairing the old ones, which of the commercially available shredders to purchase, which improvements to incinerator and disposal operations should be funded, and whether the added cost of landfill liner materials are worth the price.

A principal economic concept is that time represents money, that is, the so-called “time value of money.” Waste management is an ongoing endeavor, so funding and other resources are viewed over several years. Expensive equipment may be purchased and immediately installed, yet paid for years, even if the benefit provided by the equipment ends before payoff. Therefore the first step evaluating a project is the cash flow, which represents the time value of money. This requires that the cash receipts and disbursements (i.e., expenses) for each project be described over a specified time period.

The costs include initial costs (e.g., purchase price, setup, and installation), operation and maintenance (O&M), overhaul, and end-of-project life costs, for example, decommissioning, disassembly, and recycling. The costs are somewhat fluid and interrelated. For example, a landfill may have major decommissioning costs if hazardous substances have accumulated. Therefore O&M and surveillance costs upfront can prevent major costs over time. The disbursements include salvage value, that is, what the equipment or property is worth after its operational life, and revenues (e.g., sales of compost or recycled materials).

The cost flow diagram (CFD) is used to evaluate costs and disbursements (see Fig. 36.1).

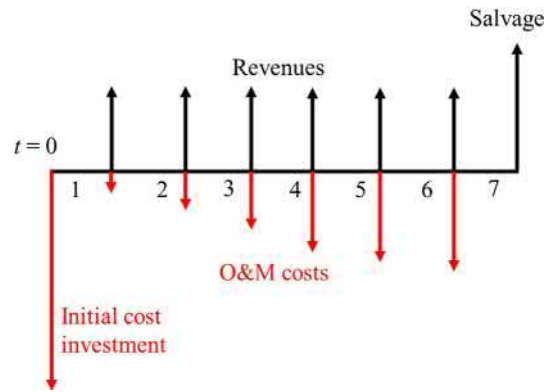


FIG. 36.1 Simple cash flow diagram. In this case, after the initial investment, revenues are constant, whereas operation and maintenance costs are increasing each year. After year 5, O&M costs exceed revenues. After year 7, the project is ended and salvage is recovered.

The CFD shows the amount and timing of individual cash flows and forms the basis for engineering economic analysis [1]. The CFD is developed by first drawing a segmented time-based horizontal line, divided into appropriate time unit. At each cash flow even, a vertical arrow points down to costs and up for revenues or benefits. For clarity, the CFD segments should be drawn to a relative scale.

The end of period t is the same as the beginning of period $(t+1)$. The beginning of period cash flows includes costs for rent, lease, and insurance payments, whereas the end-of-period cash flows are O&M, salvages, revenues, and overhauls. Deciding where $t=0$ is arbitrary, for example, when a project is analyzed, when funding is approved, or when construction begins. Note that one group's cash outflow, represented as a negative value, is another group's inflow, represented as a positive value. Incidentally, two or more cash flows in the same year should be diagrammed individually to indicate clearly the connection from the problem statement to each cash flow in the diagram.

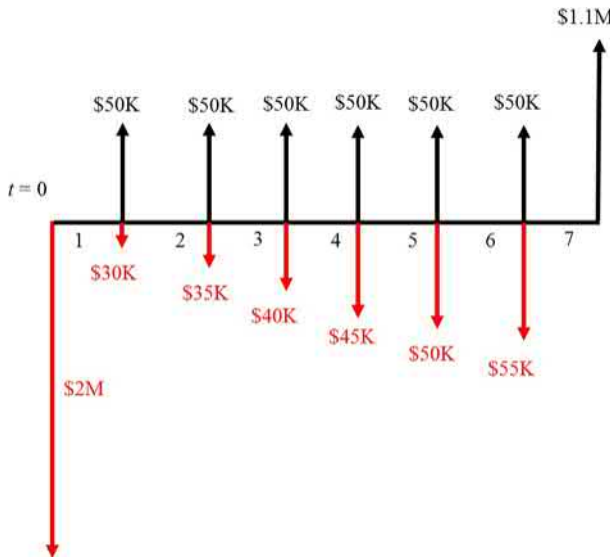


FIG. 36.2 Example cash flow diagram. In this case, after the initial investment, revenues are constant, whereas operation and maintenance costs are increasing each year. After year 5, O&M costs exceed revenues, so the project is ended and salvage is recovered.

Example: A city purchases a recycling sorting system for \$2 million, with O&M costs of \$30,000 in year 1 and increasing by \$5000 each year. Some of the sorted materials have value for a local salvage company and a plastic company, providing an annual revenue of \$50,000. After year 7, the sorter is salvaged, that is, sold to another jurisdiction, for \$110,000. To simplify, let us apply the year-end convention, that is, all expenses and revenue are assumed to occur at the end of the year. This makes the math discrete. The CFD is shown in Fig. 36.2.

2.1 Discounting

Engineering economics dictates equivalence so that all values can be compared consistently. The present worth (P) is the present amount at $t=0$. Future worth (F) is the equivalent value that will have accumulated after n periods (e.g., years) from P . The annual amount (A) is the uniform amount of money that repeats at the end of each period for n periods. If we do not assume a discrete payout, we also need to have a uniform gradient amount (G), which is the amount of

money that repeats at the end of each period, beginning at the end of period 2 and ending at the end of period n .

Therefore the CFDs can represent present value, future worth, uniform series, uniform gradient series, and exponential gradient series (see Fig. 36.3). Present value and future worth CFDs are used when determining whether a purchase is acceptable and feasible. Uniform series CFDs can be part of multiyear budgets. The two bottom CFDs in Fig. 36.3 may be more realistic for equipment and systems that demand greater maintenance and replacements. For example, if the reliability of a system declines with a linear slope, the uniform gradient series is used, but if the failure rates accelerate with time, the exponential (E) gradient CFD may be preferable.

Another important factor is the discount rate (i) that needs to be paid to borrow money, that is, the effective rate per time period. The annual i can be calculated as:

$$i = \left(1 + \frac{r}{k}\right)^{\frac{k}{p}} - 1 \quad (36.1)$$

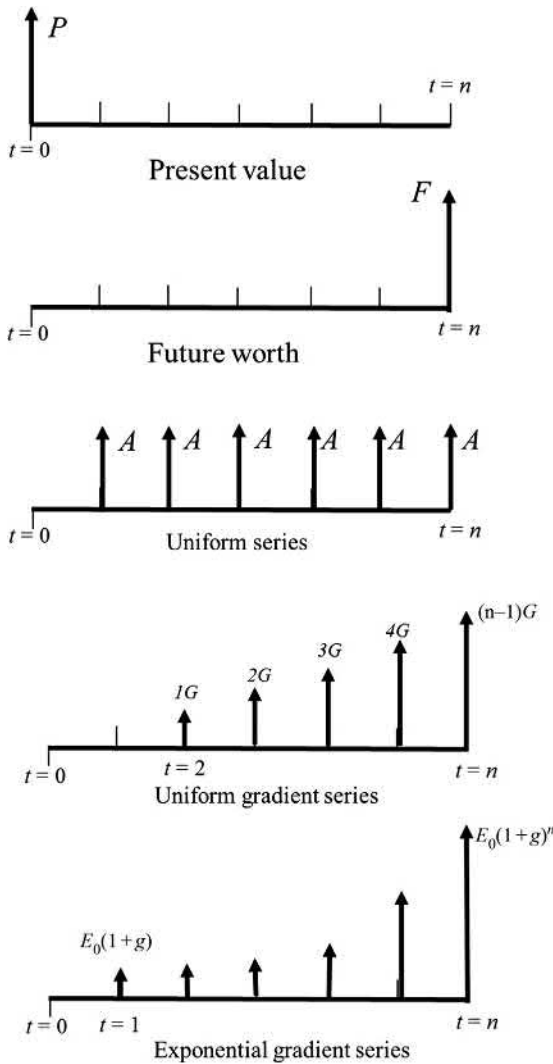


FIG. 36.3 Commonly used cash flow diagrams for waste projects.

where r = the annual interest, k = number of compounding periods per year, and p = the number of periods per year corresponding to the basis for n . Thus if payments are made monthly, $p = 12$; if daily $p = 365$.

The discounting principle states that investing P at $t = 0$ will pay F at $t = n$. Thus the discount formula is:

$$P = F (P/F, i\%, n) \quad (36.2)$$

where $(P/F, i\%, n)$ is the discount factor.

Table 36.1 provides the discount factor conversion formulae for the most common conversions for P , F , A , G , and E used by waste managers and engineers. Numerous online calculators are available for these conversions, as well as spreadsheet programs, especially Microsoft Excel (see far-right column of Table 36.1). Microsoft [2], for example, provides support for calculating, P , F , and i at:

- $P = PV(i, N, A, F, \text{Type})$: <https://support.office.com/en-us/article/PV-function-23879d31-0e02-4321-be01-da16e8168cbd>
- $F = FV(i, N, A, P, \text{Type})$: <https://support.office.com/en-us/article/FV-function-2eef9f44-a084-4c61-bdd8-4fe4bb1b71b3>
- $i = \text{RATE}(N, A, P, F, \text{Type}, \text{guess})$: <https://support.office.com/en-us/article/RATE-function-9f665657-4a7e-4bb7-a030-83fc59e748ce>

where “Type = 0” means end-of-period cash payments; “Type = 1” means beginning-of-period payments; and “guess” is the value of the interest rate.

The symbols and nomenclature are not used consistently in engineering and waste management economics. For example, public agencies may also represent present value as PV :

$$PV = \frac{B_{y_i}}{(1+r)^{y_i-y_0}} \quad (36.3)$$

where B = the annual benefit, r = the discount rate, y_i = the year the benefit occurs, and y_0 = the year to which future dollars are discounted.

Present value is similarly determined for annual cost (C):

$$PV = \frac{C_{y_i}}{(1+r)^{y_i-y_0}} \quad (36.4)$$

where y_i = the year the cost occurs.

TABLE 36.1 Conversions for Waste Management Economics of Present Value (P), Future Worth (F), Annual Amount (A), Gradient (G), and Exponential Gradient (EG)

Conversion	Symbol	Discount Factor Formula	Discount Factor Formula in Excel
Discrete compounding			
P to F	$(F/P, i\%, n)$	$(1+i)^n$	$=FV(i, n, 0, -1)$
F to P	$(P/F, i\%, n)$	$(1+i)^{-n}$	$=PV(i, n, 0, -1)$
F to A	$(A/F, i\%, n)$	$i/((1+i)^n - 1)$	$=PMT(i, n, 0, -1)$
P to A	$(A/P, i\%, n)$	$i^*(1+i)^n/((1+i)^n - 1)$	$=PMT(i, n, -1)$
A to F	$(F/A, i\%, n)$	$((1+i)^n - 1)/i$	$=FV(i, n, -1)$
A to P	$(P/A, i\%, n)$	$((1+i)^n - 1)/(i^*(1+i)^n)$	$=PV(i, n, -1)$
G to P	$(P/G, i\%, n)$	$((1+i)^n - 1)/(i^2*(1+i)^n) - n/(i^*(1+i)^n)$	$\{=NPV(i, (ROW(INDIRECT("1:"&n)) - 1))\}$
G to F	$(F/G, i\%, n)$	$((1+i)^n - 1)/i^2 - (n/i)$	$\{=(P/G, i\%, n)*(F/P, i\%, n)\}$
G to A	$(A/G, i\%, n)$	$(1/i) - n/((1+i)^n - 1)$	$\{=(P/G, i\%, n)*(A/P, i\%, n)\}$
EG to P	$(P/EG, z - 1, n)$	$(z^n - 1)/(z^n(z - 1)), z = (1+i)/(1+g)$	$=PV(z - 1, n, -1)$
Continuous compounding			
F to P	$(P/F, r\%, n)$	$e^{-r^*n} = 1/er^*n$	$=1/EXP(r^*n)$
P to F	$(F/P, r\%, n)$	er^*n	$=EXP(r^*n)$
F to A	$(A/F, r\%, n)$	$(e^r - 1)/(er^*n - 1)$	$=(EXP(r) - 1)/(EXP(r^*n) - 1)$
A to F	$(F/A, r\%, n)$	$(er^*n - 1)/(e^r - 1)$	$=(EXP(r^*n) - 1)/(EXP(r) - 1)$
P to A	$(A/P, r\%, n)$	$(e^r - 1)/(1 - e^{-r^*n})$	$=(EXP(r) - 1)/(1 - 1/EXP(r^*n))$
A to P	$(P/A, r\%, n)$	$(1 - e^{-r^*n})/(e^r - 1)$	$=(1 - 1/EXP(r^*n))/(EXP(r) - 1)$

Note: Excel formulae for $(F/G, i\%, n)$ and $(A/G, i\%, n)$ are based on the algebraic equivalence of $F/G = (P/G)*(F/P)$ and $A/G = (P/G)*(A/P)$. The discount factor symbols $(P/G, i\%, n)$, $(F/P, i\%, n)$, and $(A/P, i\%, n)$ need to be replaced with the appropriate discount factor formula listed in the table.

Modified from J. Wittwer, *Discount Factor Table for Excel: Summary of Discount Factor Formulas for TVM Calculations in Excel®*. 2018, May 17, 2018, Available from: <https://www.vertex42.com/ExcelArticles/discount-factors.html>.

Thus if the only thing of importance is money, you would not build the landfill in the example. However, large public projects fill societal needs, including increasing the capacity of existing facilities or systems, and/or improving public health, environmental quality, safety, and esthetics of neighborhoods and enhancing the performance of other existing facilities or systems.

The analysis of a large public project is conducted in stages:

1. Planning the analysis and defining its scope,
2. Performing engineering analyses of the alternatives,
3. Calculating the present value of project costs and benefits,
4. Evaluating the results—benefit-cost analysis (BCA).

Planning the BCA and performing the engineering analysis (the first two stages) require careful thought. The analysis should capture

EXAMPLE

Assume, for example, new landfill is estimated to cost \$5,000,000. Construction will occur in 2025. The year of analysis is 2020. If the discount rate is 3.6% for the year 2020, what is the present value of the construction cost?

Given: $AC = \$5,000,000$; $r = 0.036$,
 $n = 2025 - 2020 = 5$

Then, $PV = 5,000,000 / (1 + 0.036)^5$

Therefore $PV = \frac{5,000,000}{(1 + 0.036)^5} = \$244,189,587$
 (see Fig. 36.4).

The \$5 million is the present value. If the project can wait until 2025, the money could be put into a bank where it earns interest or put into other projects where it generates immediate benefits. The amount that needs to be deposited into the bank to have \$5 million in 2025, using a 3.6% discount rate, is only \$4.2 million—the present value of the cost of the project in 2020. The same logic applies to benefits.



FIG. 36.4 Discount rate example. Data from DOT, *Benefit Cost Analysis for Transportation Projects*, 2012, Available from: <https://www.dot.state.mn.us/planning/program/benefitcost.html>.

the appropriate benefits and cost differences between the Base Case and the identified Alternatives [3]. These first two stages are the most complicated and require the most time and effort. The economic calculation stage is a

relatively short and straightforward process. Evaluation and interpretation of the results requires judgment and experience. The process of conducting a BCA can be iterative: the process may require going back to a previous stage to verify results and explore subalternatives.

3 COMPARING ALTERNATIVES

Rather than simply deciding whether to accept a proposal, it is better to decide on a functional objective and then identify ways to provide that function in the most efficient and effective way. Both benefits and costs vary, so this analysis must find alternative means of maximizing net benefits and, similarly, minimizing costs to get a desired amount of benefits. This is known as the BCA, which assumes:

1. Equivalence, that is, benefits or costs are in the same units in all projects under review. Most often this monetized, for example, expressed in dollars, pounds, yen, or euros.
2. The public is the “user” or “client” who will benefit from the selected project.
3. The “sponsor” is the some level of government (e.g., town, city, county, state, province, nation, or even multinational organizations).

The analysis consists of:

1. identifying all user benefits (positive outcomes) and “disbenefits” (negative outcomes);
2. quantification and comparison of these benefits and disbenefits;
3. identification and quantification of the sponsor’s costs;
4. finding the equivalent net benefits and net costs at the base period, with a discount rate specific to the project; and,
5. consider the project “acceptable” if the equivalent user’s net benefits exceed the equivalent sponsor’s net costs (however, you

will likely want to have a rule for exceedance before the project is accepted, e.g., some percentage above).

Basically, the BCA seeks to show whether the benefits are worth the economic investment. This can be viewed at various points in the design process. For example:

- Project planning: From an economic perspective, are the benefits of constructing a landfill the project costs compared to the present waste handling system?
- Design and environmental study: From an economic perspective, are the benefits of location "A" worth the project costs? How does location "A" compare to "B" or "C"?
- Construction planning: From an economic perspective, are the benefits of closing certain lanes to a landfill during its construction worth the traffic delay and diversion costs, that is, compared to keeping some lanes open?

The BCA is most valuable after a decision is made, based on risk and reliability. It is more valuable as a tool for comparing and evaluating alternatives than for whether to provide a service. For example, if a risk assessment indicates that water is being contaminated, the BCA would not override the need to clean the water, but would seek the best and most feasible means of doing so. As discussed in [Chapter 35](#), the cleanup would have to meet a risk-based or other environmental standard. Thus the project would have to provide water that meets this standard, and the waste manager would decide which of the options for doing this are most cost effective.

The BCA is a tool for maximizing benefits for a certain amount of costs; for example, the basis for a waste management or public works budget. So, the BCA needs to be more than a financial comparison. Indeed, various methods are used for comparing benefits and costs for a public project. After deciding which

alternatives are feasible and viable, different techniques can be applied to compare them, including:

Net Present Value (NPV): NPV is the value resulting from subtracting the expected cost from the expected benefits. Projects having a NPV less than zero should be avoided.

Internal Rate of Return (IRR): the IRR is the discount rate at which the present value of costs equals the present value of benefits. Alternatively, IRR is the discount rate at which $NPV = 0$ and $BCR = 1.0$. If IRR exceeds the opportunity cost of the capital, the project is economically sound and worth pursuing [\[2\]](#).

Benefit-Cost Ratio (BCR): the BCR is the ratio of the present value of benefits to the present value of costs. A BCR is a gross tool that may serve as a screen and is part of a larger analysis. In its simplest form, it is ratio of benefits to cost of a project. For example, [Table 36.2](#) presents the scores and weights in a BCR analysis for a proposed hypothetical landfill.

The scores are weighted according to importance, so the most important factors in this case are water quality and closing dumps. Thus the benefits equal: $15 + 3 + 25 + 12 = 55$. The costs

TABLE 36.2 Hypothetical Benefit and Cost Scores and Weights

	Score	Weight	Total
<i>Benefits</i>			
Water quality	3	5	15
Gas sales	1	3	3
Removal of open dumps	5	5	25
Customer satisfaction	3	4	12
<i>Costs</i>			
Expenses	5	3	15
Fugitive dust	2	2	4
Odors	3	2	6

equal: $15+4+6=25$. Therefore this benefit-to-cost ratio is $55/25=2.2$. This may indicate that the landfill is acceptable. However, the scores and weightings are highly subjective. Such ratios are notorious for justifying previously ordained projects.

Ideally, the BCA would project and evaluate all possibilities, but this is not possible or even desirable because of the large uncertainties. So, project alternatives need to be screen. Expert judgment can be a first screen to differentiate infeasible alternatives to realistic options and compare them to a base case. The base case is not necessarily the “no action” alternative, although, in most BCAs, one or more of the other options have substantial improvements over the base case. Linear programming and other optimization techniques can be used to quantify the economic feasibility of a project from a life cycle/systems perspective. Public projects must also differentiate economic costs and benefits from other societal costs and benefits. Thus the BCA differs from an economic impact analysis (EIA). The U.S. Department of Transportation, for example, differentiates the two processes [4]:

A BCA measures the value of a project’s benefits and costs to society, while an economic impact analysis measures the impact of increased economic activity within a region. Common metrics for measuring economic impacts include retail spending, business activity, tax revenues, jobs, and property values. Economic impact analyses often take a strictly positive view, (i.e., increased jobs, spending) and do not examine how the resources used for a project might have benefitted alternative societal uses of the resources (i.e., they do not assess the net effect on society).

In this sense, an economic impact analysis would consider the initial investment in infrastructure as a stimulus to the local economy, as opposed to a cost to the local government. Also, economic impact analyses are smaller scale than the usual BCA, which usually consider broad, economy-wide and “societal”

benefits and costs. Effects in one region may be offset by losses in a neighboring region, reflecting a transfer of spending or jobs that may be a net neutral summation. Thus, the two local jurisdictions would have different economic impact results, but the BCA would not change, since its focus is larger.

4 REPLACEMENT COST ANALYSIS

As any waste manager can attest, things wear out. Replacement and repair will result; it is merely a matter of time. Often replacement applies to a “supply,” that is, something that is expected to be used and changed frequently. Repair is often seen as returning “capital equipment” to its designed efficiency.

These are semantical distinctions. Of course, any piece of a system needs to be replaced, including capital equipment. This is not always due to wear. Sometimes, the function has changed, for example, labor-intensive sorting equipment may be fine until a town’s population reaches a threshold where the equipment needs to be replaced by higher capacity equipment. Sometimes, there is a safety issue; for example, the older equipment may have met previous worker safety regulations, but no longer does. Often, however, economics drives the decision, for example, the mean time to repair (MTTR) may indicate it is time to replace equipment. Any type of asset eventually loses value and must be replaced due to:

- Obsolesce: Fast for information technology, slower for mechanical equipment
- Depletion: Supplies
- Deterioration: Mechanical equipment

Replacement cost analysis (RCA) uses specific terminology. The “defender” is the existing piece. The “challenger” is the best available replacement equipment. Current market value is the selling price of the defender in the marketplace.

There are a few ways to compare useful life, but a popular one is the equivalent uniform annual cost (EUAC).

The RCA is done in steps:

1. identify alternatives (reasonable and available), at least: Defender, ... Best challenger;
2. determine whether good defender marginal cost data are available;
3. if data are available, see if the marginal costs are increasing;
4. if increasing, then compare defender's next year marginal cost with challenger's EUAC (use Analysis Technique 1, described later);
5. if not increasing, then must find lowest EUAC for defender and compare it to the challenger's EUAC at its minimum cost life (use Analysis Technique 2, discussed later);
6. if defender marginal cost data not available, must find EUAC over given equipment life (use Analysis Technique 3; described later);
7. compare defender's EUAC over its remaining life to the challenger's EUAC at its minimum cost life;
8. calculate the EUAC for each value of the useful life (e.g., $n = 1$, $n = 2$, $n = 3$, etc.);
9. time period at which the EUAC is minimized is the minimum cost life (economic useful life).

4.1 RCA Techniques

Technique 1: If the defender marginal costs are increasing, replace when the marginal costs of ownership are more than the EUAC of the challenger. This is appropriate approach when replacement repeatability assumptions hold:

- Best challenger is available for all subsequent years and its costs will remain unchanged.
- The period of service is infinite.
- If these are too restrictive, can assume a more realistic, known, and limited project life.

Technique 2: If the replacement repeatability holds, compare the EUAC of the defender asset at its minimum cost life against the EUAC of the challenger at its minimum cost life.

Technique 3: Compare the defender's EUAC over the stated life against the minimum EUAC of the challenger. There may be a problem in defining first costs of the defender and challenger. Trade-in value is not suitable; market value is appropriate.

Any cost analysis is incomplete if it neglects tax. Thus all relevant taxes will affect the remaining life of the defender, the economic life of the challenger, and defender versus challenger comparisons. After-tax replacement depends on the depreciation Modified Accelerated Cost Recovery System (MACRS) and assets market over time [5].

REPLACEMENT COST ANALYSIS EXAMPLE

Assuming the conditions in Table 36.3 hold, we need to decide how to address failing equipment.

Goal: Narrow replacement down to one challenger.

Approach: Evaluate each candidate challengers at its minimum cost life.

This can be done using the previously discussed alternative evaluation approaches, that is, NPW, EUAC, IRR, or BCR.

Next, find minimum cost life. An asset can have several possible lives, depending on frequency of asset replacement. The life that minimizes the

asset's EUAC is known as the asset's minimum cost life.

Example:

If initial cost (P) is \$7500, arithmetic gradient maintenance cost (G) is \$900, uniform cost (A) is \$500, and arithmetic gradient operating cost (G) is \$400, at an 8% interest rate.

There is no salvage value.

The " n " is changing depending on the year, on an arithmetic gradient, that is, it is changing each year ($n = 1$; $n = 2$, ...).

The 15-year spreadsheet is presented in Table 36.4.

Continued

REPLACEMENT COST ANALYSIS EXAMPLE (cont'd)

TABLE 36.3 Defender and Challenger Example From P.R. Rosenkrantz, Cal Poly Pomona [5]

	Where		Compare	
	Defender Marginal Cost	Defender Marginal Cost	Defender	Best Challenger
1	Available	Increasing	Next-year marginal cost	EUAC at minimum cost life
2	Available	Not increasing	EUAC at minimum cost life	EUAC at minimum cost life
3	Not available		EUAC over remaining useful life	EUAC at minimum cost life

TABLE 36.4 Spreadsheet for Equivalent Uniform Annual Cost (EUAC) Example From P.R. Rosenkrantz, Cal Poly Pomona [5]

Year	EUAC of Capital Recovery Costs	EUAC of Maintenance and Repair Costs	EUAC of Operating Costs	EUAC Total	Interest Rate
Initial year	−7500	0	−500		8%
Arithmetic gradient		−900	−400		
1	\$8100.00	\$0.00	\$500.00	\$8600.00	
2	\$4205.77	\$432.69	\$692.31	\$5330.77	
3	\$2910.25	\$853.87	\$879.50	\$4643.62	
4	\$2264.41	\$1263.56	\$1061.58	\$4589.55	<—— MIN
5	\$1878.42	\$1661.82	\$1238.59	\$4778.84	
6	\$1622.37	\$2048.71	\$1410.54	\$5081.62	
7	\$1440.54	\$2424.30	\$1577.47	\$5442.31	
8	\$1305.11	\$2788.67	\$1739.41	\$5833.19	
9	\$1200.60	\$3141.93	\$1896.41	\$6238.94	
10	\$1117.72	\$3484.18	\$2048.53	\$6650.43	
11	\$1050.57	\$3815.55	\$2195.80	\$7061.93	
12	\$995.21	\$4136.17	\$2338.30	\$7469.68	
13	\$948.91	\$4446.19	\$2476.08	\$7871.18	
14	\$909.73	\$4745.75	\$2609.22	\$8264.69	
15	\$876.22	\$5035.01	\$2737.78	\$8649.02	

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REPLACEMENT COST ANALYSIS EXAMPLE *(cont'd)*

The second column can be constructed in Excel as $\$7500(A/P, 8\%, n)$. Third column: $\$900(A/P, 8\%, n)$. Fourth column: $\$500 + 400(A/P, 8\%, n)$. The fifth column is the sum of the values in columns 2, 3, and 4.

Thus the lowest total EUAC is year 4, so this is the economic useful life and minimum cost life is when $n=4$ years (see Fig. 36.5):

Next, find the year-by-year costs for keeping an asset (i.e., marginal costs). This includes loss in value of the asset for keeping it (usually per year), the lost interest from tying up funds in this asset. The costs are directly related to the asset, for example, expenses like insurance and O&M.

An example of a marginal cost comparison is presented in Table 36.5.

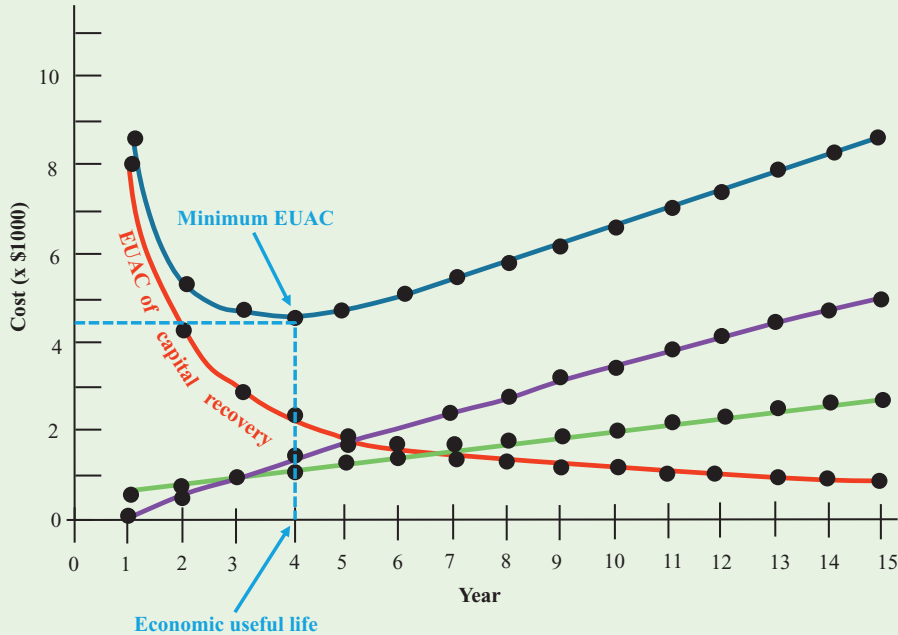


FIG. 36.5 Minimum equivalent uniform annual cost (EUAC) used to find the economic useful life. Data from P.R. Rosenkrantz, *Replacement*, 2018 (Chapter 12), Available from: https://www.cpp.edu/~rosenkrantz/egr403site/egr403online/egr403_sv15_chapter12.ppt.

TABLE 36.5 Example of a Marginal Cost Comparison Between New Equipment (A) and Exiting Equipment (B) in a Replacement Cost Analysis

A. New Item (Challenger):			
Expense	Cost	Years	Incremental Cost Thereafter
Investment cost	\$25,000.00	0	\$ –
Annual O&M cost	\$2000.00	1	\$500.00
Annual insurance cost	\$5000.00	3	\$1500.00
Useful life (years)	7		
MARR	15%		

Continued

REPLACEMENT COST ANALYSIS EXAMPLE (cont'd)

Year	Market Value	Loss in Market Value	Foregone Interest	O&M Cost	Insurance Cost	Total Marginal Cost
0	\$25,000.00					
1	\$18,000.00	\$7000.00	\$3750.00	\$2000.00	\$5000.00	\$17,750.00
2	\$13,000.00	\$5000.00	\$2700.00	\$2500.00	\$5000.00	\$15,200.00
3	\$9000.00	\$4000.00	\$1950.00	\$3000.00	\$5000.00	\$13,950.00
4	\$6000.00	\$3000.00	\$1350.00	\$3500.00	\$6500.00	\$14,350.00
5	\$4000.00	\$2000.00	\$900.00	\$4000.00	\$8000.00	\$14,900.00
6	\$3000.00	\$1000.00	\$600.00	\$4500.00	\$9500.00	\$15,600.00
7	\$2500.00	\$500.00	\$450.00	\$5000.00	\$11,000.00	\$16,950.00

B. Defender:			
Expense	Cost	Years	Incremental Cost Thereafter
Investment cost	\$15,000.00	0	\$ –
Annual O&M cost	\$10,000.00	1	\$1500.00
Annual insurance cost	\$ –		\$ –
Useful life (years)	5		
MARR	15%		

Year	Market Value	Loss in Market Value	Foregone Interest	O&M Cost	Insurance Cost	Total Marginal Cost
0	\$15,000.00					
1	\$14,000.00	\$1000.00	\$2250.00	\$10,000.00	\$ –	\$13,250.00
2	\$13,000.00	\$1000.00	\$2100.00	\$11,500.00	\$ –	\$14,600.00
3	\$12,000.00	\$1000.00	\$1950.00	\$13,000.00	\$ –	\$15,950.00
4	\$11,000.00	\$1000.00	\$1800.00	\$14,500.00	\$ –	\$17,300.00
5	\$10,000.00	\$1000.00	\$1650.00	\$16,000.00	\$ –	\$18,650.00
6						
7						

Modified from P.R. Rosenkrantz, *Replacement*, 2018 (Chapter 12), Available from: https://www.cpp.edu/~rosenkrantz/egr403site/egr403online/egr403_sv15_chapter12.ppt.

In this example, the marginal costs of the defender are constantly increasing, but the marginal costs of the challenger decrease for 3 years and then start

to increase. By year 3, the challenger marginal costs become less than the defenders and stay the way until the end of the defender's useful life (year 5).

5 LIFE CYCLE COMPARISONS

The project evaluation techniques so far have helped the waste manager select from finite alternatives. Another aspect of evaluation is improving existing systems to provide the needed function or to eliminate problems that weaken that alternative. In life cycle assessment (LCA), alternatives assessment is a formal technique to characterize the hazards of substances based on a full range of human health and environmental information [6]. Changes in the life cycle made based on these assessments ameliorate the potential for unintended consequences a priori.

The current approach for alternatives assessment presented in Table 36.6 goes beyond

hazard alternatives to address benefits and utility provided by a waste management option, that is, steps in LCA stages may require helium (He), which is becoming less available. A thorough alternative assessment may identify steps where a different, more renewable chemical or even use a nonchemical technique to perform the same function. Thus the steps in Table 36.6 may be applied to other substitutions and replacements, for example, energy use, labor and skill mix, and social justice.

Alternative assessment and other life cycle approaches could supplant many of the single approach, unsustainable approaches with more systematic, sustainable solutions. Note that Table 35.1 calls for stakeholder involvement and risk communication (see Chapter 33). For

TABLE 36.6 Key Steps in Alternatives Assessment for Substituting Toxic Chemicals in the Life Cycle of a Process

Process	Action	Application to Finite Resources
Step 1: Determine feasibility	Consider whether alternatives: 1. are commercially available and cost effective; 2. have the potential for an improved health and environmental profile; 3. are likely to result in lasting change; and 4. to what extent stakeholders are interested.	Consider whether the goods and services can be provided with lesser amounts of these resources.
Step 2: Collect information	Find data about and consider: 1. how well characterized the possible alternatives are; 2. how much is known about the chemical manufacturing process; 3. the range of functional uses that the chemical serves; 4. the feedstock of contaminants and residuals from the production process; and 5. the work of others who are exploring alternatives for the chemical of concern, similar chemicals, and functional uses. Based on analysis of this information and preliminary stakeholder consultation, develop a proposed project scope and an approach for developing the alternatives assessment.	Same, except collect market and production information.

Continued

TABLE 36.6 Key Steps in Alternatives Assessment for Substituting Toxic Chemicals in the Life Cycle of a Process—cont'd

Process	Action	Application to Finite Resources
Step 3: Convene stakeholders	Stakeholders are drawn from entire supply chain and all life cycle stages of the chemical of concern. Involvement throughout the project helps to ensure that stakeholders contribute to, understand and support the outcome, enhancing credibility and promoting adoption of the safer alternatives. Typical stakeholders include chemical manufacturers, product manufacturers, nongovernmental organizations, government agencies, academics, retailers, consumers, and waste and recycling companies. Chemical and technology innovators are critical members of the group.	Same process, but include additional stakeholders, for example, from similar industries.
Step 4: Identify viable alternatives	Collect information about viability on a range of potential alternatives. The focus is on finding alternatives that are functional with minimum disruption to the manufacturing process. To identify the most likely alternatives, may also include viability demonstrations by chemical and product manufacturers.	Same.
Step 5: Conduct hazard assessment	Based on the best data that are available from the literature or can be modeled, assign an adjective descriptor of hazard concern level of high, moderate, or low for each alternative across a range of endpoints, including acute and repeated dose toxicity, carcinogenicity and mutagenicity, reproductive and developmental toxicity, neurotoxicity, sensitization and irritation, acute and chronic aquatic toxicity, and persistence and bioaccumulation. In addition, we provide a qualitative description of potential endocrine activity.	Rather than an assessment solely of potential hazards, include potential substitutions and utility of these substitutions in terms of providing the same goods and services as current processes.

Source: [7]; data for two left columns from: [8]; right column [9, 10].

example, using expert elicitation techniques with other jurisdictions, universities and governance to identify ways to eliminate the use of toxic chemicals before they reach the waste stream [11].

Although expert judgment is almost always applied at the outset of project evaluation, for example, deciding which alternatives are not worthy of further scientific investigation, it is also useful as the evaluation continues. Project evaluation can be a protracted, lengthy, and iterative

process. Indeed, there may come a point where decision makers ask the waste manager to “settle” on a less-than-optimal approach. In addition, after substantial time and psychic investment in narrowing down the alternative list to a few, well-understood options, it may be difficult to be completely objective. This may be a good time to bring in someone “cold” who can view the options more systematically and advise the waste manager as to whether the original functions and objectives are being met.

6 CONCLUSIONS

Comparing public waste projects exists in two distinct domains: scientific credibility and economic feasibility. Most of the chapters in this book have addressed the former. This chapter has considered the ways to do the latter and to incorporate economic efficiencies with considerations of risk, reliability, and resilience. Economic acceptability is useless if a project fails to meet standards of performance based on public health, environmental quality, and societal acceptance.

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Epilogue

Our journey from exploitation to sustainability has taken us along many paths and for the moment it is complete. We see that over the past 20 years many new areas of expertise have been developed and much energy has been expended to contain old and the new waste forms. Here are some reflections on the questions asked in the Prologue:

1. How much is known about each waste stream? What is the state of the science?

The difference between our first and second editions shows that the scientific underpinning of sound waste management continues to grow. Every chapter indicates how knowledgebases supporting decisions about the the various waste streams are becoming more reliable, yet new challenges call for ever-improving data.

2. What levels of certainty are needed to take actions?

Vallero has argued that we have moved from the primacy of acceptable risk to acceptable uncertainty. Waste management is an effort to find optimal solutions to minimize risk while assuring that the solutions are sustainable, reliable and resilient. Of course, manager, scientists, and engineers strive to reduce uncertainty, but know that every waste decision is inherently uncertain. Waiting to address a problem to achieve maximal certainty is itself a decision. Indeed, it is a decision that has traded off improved certainty at the expense of exposure to ongoing risk. Each chapter has specified

different levels of acceptable uncertainty to accompany risk reduction.

3. How do the various professional and scientific disciplines vary in their approaches?

Perhaps, one of the most obvious conclusion to even a passive reader of this book is that waste management is highly eclectic. Of course, engineers apply sound science in nearly every chapter, but the manner of these applications vary considerably. Arguably, every chapter could be expanded to a book dedicated to a particular waste stream or approach.

4. How should waste decisions be evaluated?

There is at least one universal metric for evaluating a waste decision, i.e. its success in reducing risks to human health and the environment. However, even this is fraught with uncertainty since risks are often subtle and may unfold very slowly. This book has strived to add other decision metrics, including sustainability, reliability, resilience, and precaution. Furthermore, those who evaluate the decision will have their own metrics. Other departments within the same authority will differ from those that implement waste management solutions. Lawyers, health officials, city managers, and the general public will likely apply very different criteria on the extent to which a waste decision is successful. This book has strived to consider a wide swath, but the waste practitioner should not be surprised to be criticized for what seems to be an unassailable, scientifically sound decision.

5. What constitutes best practices in waste management?

We end our book with such practices, but they are incorporated throughout. Certainly, meeting regulatory mandates and standards is obligatory, but best practices often must surpass these minimums. Best practices must also balance the physical, biological and social sciences. Best practices must adhere to sound principles, but go beyond then to address unique or localized waste problems. Best practices must provide lasting solutions, which may mean that upfront costs may be higher than what bosses and budgeteers will like. Best practices require that the waste manager hold paramount the safety, health and welfare of the public. As such, best practices are usually not easy. Often, the trusty engineering manuals and handbooks are merely the foundation from which best practices will emerge.

Waste management is an inexact science that attempts to be as exact as possible in addressing ill-posed problems. That is part of the reason

that this book is more about guidance than about “plug and chug” tools. Best practices must be tailored to the specific conditions of each waste. Managing wastes is decision-making with large uncertainties about numerous variables. Thus waste management is at once exciting and frightening. The famous engineer, Norm Augustine, has put this dichotomy in perspective [1]:

The bottom line is that the things engineers do have consequences, both positive and negative, sometimes unintended, often widespread, and occasionally irreversible... Engineers who make bad decisions often don't know they are confronting ethical issues.

Thus waste management is not only a technically challenging and exciting endeavor, but it is also a moral imperative.

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WASTE

A Handbook for Management

Edited by Trevor M. Letcher and Daniel A. Vallero

Waste: A Handbook for Management, Second Edition, provides scientific, engineering, and operational guidance covering a wide range of best practices, as well as hot topics and emerging areas related to waste, such as hydraulic fracturing, plastics and microplastics, waste management in developing countries, and waste-exposure-outcome pathways. Beginning with an overview of the current waste landscape; notably green engineering, processing principles, and regulations, the book then outlines waste streams and treatment methods for over 25 different types of waste. It provides ample reviews of best practices and management techniques, including the challenges for developing countries. The best practice discussions build on proven technologies and approaches based on risk, reliability, and resilience of waste management systems that consider complete contaminant pathways and risk trade-offs.

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Trevor M. Letcher is Emeritus Professor of Chemistry at the University of KwaZulu-Natal, Durban, South Africa. His widely published research involves the thermodynamics of liquid mixtures and energy from landfill. He has also edited books on *Climate Change*, *Future Energy*, *Storing Energy*, *Wind Energy*, and *Solar Energy*. He is the editor-in-chief of Elsevier's nine volume series entitled *Comprehensive Renewable Energy* and he, together with Vallero, wrote *Unraveling Environmental Disasters*.

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