30

Preventing Air Pollution

I. INTRODUCTION

The *green* professional is no longer a term for a neophyte to the profession (opposite of a "grey beard"). It is now more likely to mean an environmentally oriented engineer, scientist, planner, or other environmental decision maker. In fact, green engineering is simply systematic engineering done well. If a process is considered comprehensively and systematically, many of the expenses and social costs of air pollution can be prevented. This is always preferable to treating and controlling the problems, which is the subject of the next few chapters.

We can begin understanding air pollution prevention by considering the concept of *sustainability*.

II. SUSTAINABILITY

Their recognition of an impending global threat of environmental degradation led the World Commission on Environment and Development, sponsored by the United Nations, to conduct a study of the world's resources. Also known as the Brundtland Commission, their 1987 report, *Our Common Future,* introduced the term *sustainable development* and defined it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. The United Nations Conference on Environment and Development (UNCED), i.e. 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 (WSSD) identified five major areas that are considered key for moving sustainable development plans forward.

The underlying purpose of sustainable development is to help developing nations manage their resources, such as rain forests, without depleting these resources and making them unusable for future generations. In short, the objective is to prevent the collapse of the global ecosystems. The Brundtland report presumes that we have a core ethic of intergenerational equity, and that future generations should have an equal opportunity to achieve a high quality of life. The report is silent, however, on just why we should embrace the ideal of intergenerational equity, or why one should be concerned about the survival of the human species. The goal is a sustainable global ecologic and economic system, achieved in part by the wise use of available resources.

From a thermodynamics standpoint, a sustainable system is one that is in equilibrium or changing at a tolerably slow rate. In the food chain, for example, plants are fed by sunlight, moisture and nutrients, and then become food themselves for insects and herbivores, which in turn act as food for larger animals. The waste from these animals relenishes the soil, which nourishes plants, and the cycle begins again [2].

"Sustainable design" is a systematic approach. At the largest scale, manufacturing, transportation, commerce and other human activities that promote high consumption and wastefulness of finite resources cannot be sustained. At the individual designer scale, the products and processes must be considered for their entire lifetimes and beyond.

III. GREEN ENGINEERING AND SUSTAINABILITY

To attain sustainability, people need to adopt new and better means of using materials and energy. The operationalizing of the quest for sustainability is defined as *green engineering,* a term that recognizes that engineers are central to the practical application of the principles sustainability to everyday life [3].

The relationship between sustainable development, sustainability, and green engineering can be depicted as:

Sustainable development → Green engineering → Sustainability

Sustainable development is an ideal that can lead to sustainability, but this can only be done through green engineering.

Green engineering [4] treats environmental quality as an end in itself. The US EPA has defined green engineering as:

> ... the design, commercialization, and use of processes and products, which are feasible and economical while minimizing (1) generation of pollution at the source and (2) risk to human health and the environment. The discipline embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost effectiveness when applied early to the design and development phase of a process or product [5].

Green engineering approaches are being linked to improved computational abilities (see Table 30.1) and other tools that were not available at the outset of the environmental movement. Increasingly, companies have come to recognize that improved efficiencies save time, money, and other resources in the long run. Hence, companies are thinking systematically about the entire product stream in numerous ways:

- applying sustainable development concepts, including the framework and foundations of "green" design and engineering models;
- applying the design process within the context of a sustainable framework: including considerations of commercial and institutional influences;
- considering practical problems and solutions from a comprehensive standpoint to achieve sustainable products and processes;
- characterizing waste streams resulting from designs;
- understanding how first principles of science, including thermodynamics, must be integral to sustainable designs in terms of mass and energy relationships, including reactors, heat exchangers, and separation processes;
- applying creativity and originality in group product and building design projects.

There are numerous industrial, commercial, and governmental green initiatives, including design for the environment (DFE), design for disassembly (DFD), and design for recycling (DFR) [6]. These are replacing or at least changing pollution control paradigms. For example, concept of a "cap and trade" has been tested and works well for some pollutants. This is a system where companies are allowed to place a "bubble" over a whole manufacturing complex or trade pollution credits with other companies in their industry

TABLE 30.1

Principles of Green Programs. First Two Columns, Except "Nano-materials"

Principle	Description	Example	Role of computational toxicology
Waste prevention	Design chemical syntheses and select processes to prevent waste, leaving no waste to treat or clean up.	Use a water-based process instead of an organic solvent-based process.	Informatics and data mining can provide candidate syntheses and processes.
Safe Design	Design products to be fully effective, yet have little or no toxicity.	Using microstructures, instead of toxic pigments, to give color to products. Microstructures bend, reflect and absorb light in ways that allow for a full range of colors.	Systems biology and "omics" (genomics, proteomics, and metabonomics) technologies can support predictions of cumulative risk from products used in various scenarios.
Low hazard chemical synthesis	Design syntheses to use and generate substances with little or no toxicity to humans and the environment.	Select chemical synthesis with toxicity of the reagents in mind upfront. If a reagent ordinarily required in the synthesis is acutely or chronically toxic, find another reagent or new reaction with less toxic reagents.	Computational chemistry can help predict unintended product formation and reaction rates of optional reactions.
Renewable material use	Use raw materials and feedstocks that are renewable rather than those that deplete nonrenewable natural resources. Renewable feedstocks are often made from agricultural products or are the wastes of other processes; depleting feedstocks are made from fossil fuels (petroleum, natural gas, or coal) or that must be extracted by mining.	Construction materials can be from renewable and depleting sources. Linoleum flooring, for example, is highly durable, can be maintained with nontoxic cleaning products, and is manufactured from renewable resources amenable to being recycled. Upon demolition or re-flooring, the linoleum can be composted.	Systems biology, informatics, and "omics" technologies can provide insights into the possible chemical reactions and toxicity of the compounds produced when switching from depleting to renewable materials.
Catalysis	Minimize waste by using catalytic reactions. Catalysts are used in small amounts and can carry out a single reaction many times. They are preferable	The Brookhaven National Laboratory recently reported that it has found a "green catalyst" that works by removing one stage of the reaction, eliminating the need to use solvents	Computation chemistry can help to compare rates of chemical reactions using various catalysts.

TABLE 30.1 (*Continued*)

Principle	Description	Example	Role of computational toxicology
	to stoichiometric reagents, which are used in excess and work only once.	in the process by which many organic compounds are synthesized. The catalyst dissolves into the reactants. Also, the catalyst has the unique ability of being easily removed and recycled because, at the end of the reaction, the catalyst precipitates out of products as a solid material, allowing it to be separated from the products without using additional chemical solvents.[a]	
Avoiding chemical derivatives	Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.	Derivativization is a common analytical method in environmental chemistry, i.e. forming new compounds that can be detected by chromatography. However, chemists must be aware of possible toxic compounds formed, including left over reagents that are inherently dangerous.	Computational methods and natural products chemistry can help scientists start with a better synthetic framework.
Atom economy	Design syntheses so that the final product contains the maximum proportion of the starting materials. There should be few, if any, wasted atoms.	Single atomic and molecular scale logic used to develop electronic devices that incorporate DFD, DFR, and design for safe and environmentally optimized use.	The same amount of value, e.g. information storage and application, is available on a much smaller scale. Thus, devices are smarter and smaller, and more economical in the long-term. Computational toxicology enhances the ability to make product decisions with better predictions of possible adverse effects, based on the logic.
Nano-materials	Tailor made materials and processes for	Emissions, effluent, and other environmental	Improved, systematic catalysis in emission

(*Continued*)

TABLE 30.1 (*Continued*)

Principle	Description	Example	Role of computational toxicology
	specific designs and intent at the nanometer scale (≤100 nm).	controls; design for extremely long life cycles. Limits and provides better control of production and avoids over-production (i.e. "throwaway economy").	reductions, e.g. large sources like power plants and small sources like automobile exhaust systems. Zeolite and other sorbing materials used in air pollution treatment and emergency response situations can be better designed by taking advantage of surface effects; this decreases the volume of material used.
Selection of safer solvents and reaction conditions	Avoid using solvents, separation agents, or other auxiliary chemicals. If these chemicals are necessary, use innocuous chemicals.	Supercritical chemistry and physics, especially that of carbon dioxide and other safer alternatives to halogenated solvents are finding their way into the more mainstream processes, most notably dry cleaning.	To date, most of the progress has been the result of wet chemistry and bench research. Computational methods will streamline the process, including quicker "scale-up."
Improved energy efficiencies	Run chemical reactions and other processes at ambient temperature and pressure whenever possible.	To date, chemical engineering and other reactor-based systems have relied on "cheap" fuels and, thus, have optimized on the basis of thermodynamics. Other factors, e.g. pressure, catalysis, photovoltaics and fusion, should also be emphasized in reactor optimization protocols.	Heat will always be important in reactions, but computational methods can help with relative economies of scale. Computational models can test feasibility of new energy efficient systems, including intrinsic and extrinsic hazards, e.g. to test certain scale-ups of hydrogen and other economies. Energy behaviors are scale-dependent. For example, recent measurements of H_2SO_4 bubbles when reacting with water have temperatures in range of those found the surface of the sun.[b]
Design for degradation	Design chemical products to break down to innocuous substances after use	Biopolymers, e.g. starch-based polymers can replace styrene and other halogen-based	Computation approaches can simulate the degradation of substances as they enter

TABLE 30.1 (*Continued*)

Principle	Description	Example	Role of computational toxicology
	so that they do not accumulate in the environment.	polymers in many uses. Geopolymers, e.g. silane-based polymers, can provide inorganic alternatives to organic polymers in pigments, paints, etc. These substances, when returned to the environment, become their original parent form.	various components of the environment. Computational science can be used to calculate the interplanar spaces within the polymer framework. This will help to predict persistence and to build environmentally friendly products, e.g. those where space is adequate for microbes to fit and biodegrade the substances.
Real-time analysis to prevent pollution and concurrent engineering	Include in-process real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts.	Remote sensing and satellite techniques can provide be linked to real-time data repositories to determine problems. The application to terrorism using nano-scale sensors is promising.	Real-time environmental mass spectrometry can be used to analyze whole products, obviating the need for any further sample preparation and analytical steps. Transgenic species, while controversial, can also serve as biological sentries, e.g. fish that change colors in the presence of toxic substances.
Accident prevention	Design processes using chemicals and their forms (solid, liquid, or gas) to minimize the potential for chemical accidents including explosions, fires, and releases to the environment.	Scenarios that increase probability of accidents can be tested.	Rather than waiting for an accident to occur and conducting failure analyses, computational methods can be applied in prospective and predictive mode; that is, the conditions conducive to an accident can be characterized computationally.

[a] US Department of Energy, *Research News*, http://www.eurekalert.org/features/doe/2004-05/dnl-brc050604.php; accessed on March 22, 2005.

[b] Flannigan, D. J., and Suslick, K. S., Plasma formation and temperature measurement during single-bubble cavitation. *Nature* **434**, 52–55 (2005).

Source: Adapted from US Environmental Protection Agency, 2005, *Green Chemistry*: http://www.epa.gov/greenchemistry/principles.html; accessed on April 12, 2005. Other information from discussions with Michael Hays, US EPA, National Risk Management Research Laboratory, April 28, 2005.

instead of a "stack-by-stack" and "pipe-by-pipe" approach, i.e. the so-called "command and control" approach. Such policy and regulatory innovations call for some improved technology-based approaches as well as better quality-based approaches, such as leveling out the pollutant loadings and using less expensive technologies to remove the first large bulk of pollutants, followed by higher operation and maintenance (O&M) technologies for the more difficult to treat stacks and pipes. But, the net effect can be a greater reduction of pollutant emissions and effluents than treating each stack or pipe as an independent entity. This is a foundation for most sustainable design approaches, i.e. conducting a life cycle analysis, prioritizing the most important problems, and matching the technologies and operations to address them. The problems will vary by size (e.g. pollutant emission rates), difficulty in treating, and feasibility. The easiest ones are the big ones that are easy to treat (so-called "low hanging fruit"). These improvements are relatively easy to bring about in a short time period. However, the most intractable problems are often those that are small but very expensive and difficult to control, i.e. less feasible. The expectations of the client, the regulators, and those of the individual engineer must be realistic in how rapidly the new approaches can be incorporated.

Historically, air pollution considerations have been approached by engineers as constraints on their designs. For example, hazardous substances generated by a manufacturing process were dealt with as a waste stream (including releases and emissions from vents and stacks) that must be contained and treated. The pollutant generation had to be constrained by selecting certain manufacturing types, increasing waste handling facilities, and if these did not entirely do the job, limiting rates of production. Green engineering emphasizes that these processes are often inefficient financially and environmentally, calling for a comprehensive, systematic life cycle approach. Green engineering attempts to achieve four goals:

1. Waste reduction
2. Materials management
3. Pollution prevention
4. Product enhancement

Waste reduction involves finding efficient material uses. It is compatible with other engineering efficiency improvement programs, such as total quality management and real-time or just-in-time manufacturing. The overall rationale for waste reduction is that if materials and processes are chosen intelligently at the beginning, less waste will result. In fact, a relatively new approach to engineering is to design and manufacture a product simultaneously rather than sequentially, known as *concurrent engineering*. Combined with DFE and life cycle analysis, concurrent engineering approaches may allow air quality improvements under real-life, manufacturing conditions. However, changes made in any step must consider possible effects on the rest of the design and implementation.

CASE STUDY BOX: INDOOR AIR POLLUTION AND CONCURRENT ENGINEERING FAILURE

One of the most perplexing and tragic medical mysteries of the past 50 years has been sudden infant death syndrome (SIDS). The syndrome was first identified in the early 1950s.

Numerous etiologies have been proposed for SIDS, including a number of environmental causes. Air pollution is one of the likely suspects. A recent study, for example, found a statistically significant link between exposure of newborn infants to fine aerosols and SIDS [7]. The study found that approximately 500 of the 3800 SIDS cases in 1994 were associated with elevated concentrations of particle matter with aerodynamic diameters less than $10\,\mu m$ (PM_{10}) in the United States. This estimate is based only on metropolitan areas in counties with standard PM_{10} monitors. Based on the metropolitan area with the lowest particle concentrations, there appears to be a threshold, that is, particulate-related infant deaths occurred when PM_{10} levels below $11.9\,\mu g\,m^{-3}$.

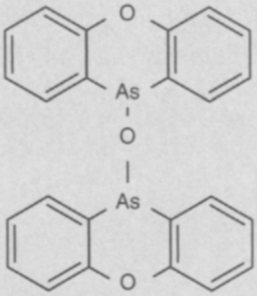
Extrapolations from these data show that almost 20% of all SIDS cases each year in the top twelve most polluted metro areas in the United States are associated with PM_{10} pollution. The number of annual SIDS cases associated with PM_{10} in Los Angeles, New York, Chicago, Philadelphia, and Detroit metropolitan areas range from 20 to 44. The study found that 10 states accounted for more than 60% of the particle-related SIDS cases, with 93 in California, 37 in Texas, and 32 in Illinois.

Since particle matter has been linked to SIDS cases, a logical extension would be to suspect the role of environmental tobacco smoke (i.e. "side stream" exposure) in some cases, since this smoke contains both particulate and gas phase contaminants that are released into the infant's breathing zone. Also, *in utero* exposures to toxic substances when a pregnant woman smokes (e.g. nicotine and other organic and inorganic toxins) may make the baby more vulnerable.

Another suspected etiology for SIDS is the exposure to pollutants via consumer products. For example, polyvinyl chloride (PVC) products have been indirectly linked to SIDS. The most interesting link is not the PVC itself, but the result of an engineering "solution."

Plastics came into their own in the 1950s, replacing many other substances, because of their lightweight and durability. However, being a polymer, physical and chemical conditions affect the ability of PVC to stay "hooked together." This can be a big problem for plastics used for protection, such as waterproofing. One such use was as a tent material.

Serendipity often plays a role in linking harmful effects to possible causes. In 1988, Barry Richardson was in the process of renting a tent for his daughter's wedding. Richardson, an expert in material science and deterioration, while renting a tent from proprietor Peter Mitchell inquired about its durability and found that PVC tents tend to break down. Richardson surmised that the rapid degradation was microbial and in fact due to fungi. The tent manufacturers decided to correct the PVC durability by changing the manufacturing process, that is, by concurrent engineering. In this case, they decided to increase the amount of fungicide, 10-10′-oxybis(phenoxarsine) (OBPA):



A quick glance at the OBPA structure shows that when it breaks down it is likely to release arsenic compounds. In this case, it is arsine (AsH_3), a toxic gas (vapor pressure = 11 mmHg at 20 °C). It is rapidly absorbed when inhaled, and easily crosses the alveolo-capillary membrane and enters red blood cells. Arsine depletes the reduced glutathione content of red blood cells, leading to the oxidation of sulfhydryl groups in hemoglobin and, possibly, red cell membranes. These effects produce membrane instability with rapid and massive intravascular hemolysis. It also binds to hemoglobin, forming a metalloid-hemaglobin complex [8]. These can lead to acute cardiovascular, neurotoxic, and respiratory effects.

Increasing the OBPA to address the problem of PVC disintegration is an example of the problem of ignoring the life cycle and systematic aspects of most engineering problems. In this case, production and marketing would greatly benefit from a type of PVC that does not break down readily under ambient conditions. In fact, if that problem cannot be solved, the entire camping market might be lost, since fungi are ubiquitous in the places where these products are used.

Had the engineers and planners considered the chemical structure and the possible uses, however, they at least might have restricted the PVC treated with high concentrations of OBPA to certain uses, such as only on tent materials, and not in materials that come in contact or near humans (bedding materials, toys, etc.). To the contrary, the PVC manufacturers blatantly disregarded the science. Richardson, the expert, from the outset had warned that increasing the amount of fungicide would not only increase the hazard and risk, but also would make the product less efficacious (even more vulnerable to fungal attack). He stated, "The biocide won't kill this fungus—instead, the fungus will consume the biocide as well as the plasticizer. Since the biocide contains arsenic, the fungus will generate a very poisonous gas which would be harmful to your staff working with the marquees." Plasticizers are semivolatile organic compounds (e.g. phthalates) that can serve as a food source for microbes, once they become acclimated. The engineers should have known this, since it is one of the biological principles upon which much wastewater treatment is based. But, the manufacturers wanted to approach the situation as a linear problem with a simple solution, that is, increase fungicide and decrease fungus. The PVC manufacturer even argued that the fungicide was even approved for use in baby mattresses.

The extent to which arsine gas released by the degradation of OBPA was a causative agent in SIDS cases is a matter of debate. But, the physics and chemistry certainly indicate that a toxic gas *could* be released leading to exposures of a highly susceptible population (babies) is not debatable.

Pollution and consumer products are only some of the possible causes of SIDS. Others include breathing position (probably increased carbon dioxide inhalation), poor nutrition, and physiological stress (e.g. overheating) [9].

The overall lesson is that are many advantages to concurrent engineering, such as real-time feedback between design and build stages, adaptive approaches, and continuous improvement. However, concurrent engineering works best when the entire life cycle is considered. The designer must ask how even a small change to improve one element in the process can affect other steps and systems within the design and build process.

IV. LIFE CYCLE ANALYSIS

One means of understanding questions of material and product use and waste production is to conduct what has become known as a *life cycle assessment*. Such an assessment is a comprehensive approach to pollution prevention by analyzing the entire life of a product, process or activity, encompassing raw materials, manufacturing, transportation, distribution, use, maintenance, recycling, and final disposal. In other words, assessing its *life cycle* should yield a complete picture of the environmental impact of a product.

The first step in a life cycle assessment is to gather data on the flow of a material. Once the quantities of various components of such a flow are known, the environmental effect of each step in the production, manufacture, use, and recovery/disposal is estimated.

Life cycle analyses are performed for several reasons, including the comparison of products for purchasing and a comparison of products by industry. In the former case, the total environmental effect of glass returnable bottles, for example, could be compared to the environmental effect of non-recyclable plastic bottles. If all of the factors going into the manufacture, distribution, and disposal of both types of bottles are considered, one container might be shown to be clearly superior.

Life cycle analyses often suffer from a dearth of data. Some of the information critical to the calculations is virtually impossible to obtain. For example, something as simple as the tonnage of solid waste collected in the United States is not readily calculable or measurable. And even if the data *were* there, the procedure suffers from the unavailability of a single accounting system. Is there an optimal level of pollution, or must all pollutants be removed 100% (a virtual impossibility)? If there is air pollution and water pollution, how must these be compared?

A recent study supported by the US EPA developed complex models using principles of life cycle analysis to estimate the cost of materials recycling. The models were able to calculate the dollar cost, as well as the cost in environmental damage caused at various levels of recycling. Contrary to intuition, and the stated public policy of the US EPA, it seems that there is a breakpoint at about 25% diversion. That is, as shown in Fig. 30.1, the cost in dollars and adverse environmental impact start to increase at an exponential rate at about 25% diversion. Should we therefore even strive for greater

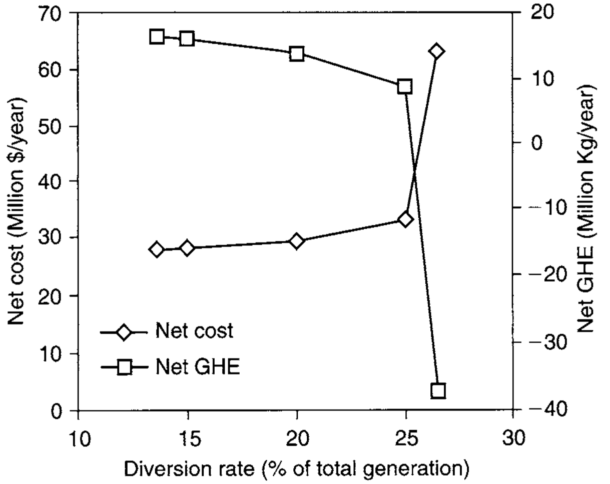


Fig. 30.1. The cost in dollars and adverse environmental impact increases dramatically when the fraction of solid waste recycled exceeds 25%. *Source*: Solano. E., Dumas, R. D., Harrison, K. W., Ranjithan, S., Barlaz, M. A., and Brill, E. D., *Integrated Sold Waste Management Using a Life-Cycle Methodology for Considering cost, Energy, and Environmental Emissions -2. Illustrative Applications.* Department of Civil Engineering, North Carolina State University, Raleigh, NC, 1999.

DISCUSSION BOX: THE MORNING CONTAINER

A simple example of the difficulties in life cycle analysis would be in finding the solution to the great coffee cup debate—whether to use paper coffee cups or polystyrene coffee cups. The answer most people would give is not to use either, but instead to rely on the permanent mug. But there nevertheless are times when disposable cups are necessary (e.g. in hospitals), and a decision must be made as to which type to choose [10]. So let us use life cycle analysis to make a decision.

The paper cup comes from trees, but the act of cutting trees results in environmental degradation. The foam cup comes from hydrocarbons such as oil and gas and this also results in adverse environmental impact, including the use of nonrenewable resources. The production of the paper cup results in significant water pollution while the production of the foam cup contributes essentially no water pollution. The production of the paper cup results in the emission of chlorine, chlorine dioxide, reduced sulfides and particulate, while the production of the foam cup results in none of these. The paper cup does not require chlorofluorocarbons (CFCs), but neither do the newer foam cups ever since the CFCs in polystyrene were phased out. The foam cups however results in the emission of pentane while the paper cup contributes none. From a materials separation perspective, the ability to recycle the foam cup is much higher than that of the paper cup since the latter is made from several materials, including the plastic coating on the paper. They both burn well, although the foam cup produces 17200 Btu lb^{-1} (40000 kJ kg^{-1}) while the paper cup produces only 8600 Btu lb^{-1} (20000 kJ kg^{-1}). In the landfill, the paper cup degrades into CO_2 and CH_4, both greenhouse gases, while the foam cup is inert. Since it is inert, it will remain in the landfill for a very long time, while the paper cup will eventually (but very slowly) decompose. If the landfill is considered a waste storage receptacle, then the foam cup is superior, since it does not participate in the reaction, while the paper cup produces gases and probably leachate. If on the other hand the landfill is thought of as a treatment facility, then the foam cup is highly detrimental since it does not biodegrade.

So, then, which cup is better for the environment? If you wanted to do the right thing, which cup should you use? Private individuals can of course practice pollution prevention by such a simple expedient as not using either plastic or paper disposable coffee cups but by using a refillable mug instead. The argument as to which kind of cup, plastic or paper, is better is then moot. It is better not to produce the waste in the first place. In addition, the coffee tastes better from a mug! Of course, the life cycle of the mug must also be factored into the decision (e.g. do the glazes contain toxic metals or were toxic materials and fossil fuels used?) This is an example of considering the function, not simply selecting a preferred device or product.

diversion rates, if this results in unreasonable cost in dollars and actually does harm to the environment?

Once the life cycle of a material or product has been analyzed, the next engineering step is to manage the life cycle. If the objective is to use the least energy and to cause the least detrimental effect on the environment, then it is clear that much of the onus is on the manufacturers of these products. The users of the products can have the best intentions for reducing adverse environmental effects, but if the products are manufactured in such a way as to make this impossible, then the fault is with the manufacturers. On the other hand, if the manufactured materials are easy to separate and recycle, then most likely energy is saved and the environment is protected. This process has become known as *pollution prevention* in industry, and there are numerous examples of how industrial firms have reduced emissions or the production of other wastes, or have made it easy to recover waste products, and in the process saved money. Some automobile manufacturers, for example, are modularizing the engines so that junked parts can be easily reconditioned and reused. Printer cartridge manufacturers have found that refilling cartridges with ink or toner is far cheaper than remanufacturing them, and now offer trade-ins. All of the efforts by industry to reduce waste (and save money in the process) will influence the solid waste stream in the future.

V. POLLUTION PREVENTION

The EPA defines "pollution prevention" as the following:

> The use of materials, processes, or practices that reduce or eliminate the creation of pollutants or wastes at the source. It includes practices that reduce the use of hazardous materials, energy, water or other resources and practices that protect natural resources through conservation or more efficient use [11].

In the widest sense, pollution prevention is the idea of eliminating waste, regardless of how this might be done.

Originally, pollution prevention was applied to industrial operations with the idea of reducing either the amount of the wastes being produced or to change their characteristics in order to make them more readily disposable. Many industries changed to water-soluble paints, for example, thereby eliminating organic solvents, clean up time, etc. and often in the process saving considerable money. In fact, the concept was first introduced as "pollution prevention pays," emphasizing that many of the changes would actually save the companies money. In addition, the elimination or reduction of hazardous and otherwise difficult wastes also has a long-term effect—it reduces the liability the company carries as a consequence of its disposal operations.

With the passage of the Pollution Prevention Act of 1990, the EPA was directed to encourage pollution prevention by setting appropriate standards for pollution prevention activities, to assist federal agencies in reducing wastes generated, to work with industry and to promote the elimination of wastes by creating waste exchanges and other programs, seek out and eliminate barriers to the efficient transfer of potential wastes, and to do this with the cooperation of the individual states.

In general, the procedure for the implementation of pollution prevention activities is to:

1. recognize a need,
2. assess the problem,
3. evaluate the alterative,
4. implement the solutions.

Contrary to most pollution control activities, industries generally have welcomed this governmental action, recognizing that pollution prevention can and often does result in the reduction of costs to the industry. Thus, recognition of the need quite often is internal and the company seeks to initiate the pollution prevention procedure.

During the assessment phase, a common procedure is to perform a "waste audit," which is the black box mass balance, using the company as the black box.

EXAMPLE BOX: WASTE AUDIT[1]

A manufacturing company is concerned about the air emissions of volatile organic carbons. These chemicals can volatilize during the manufacturing process, but the company is not able to estimate accurately the rate of volatilization, or even which chemicals are going to the vapor phase. The company conducts an audit of three of their most widely used volatile organic chemicals, with the following results:

Purchasing department records

Material	*Purchase quantity (barrels)*
Carbon tetrachloride[2] (CCl_4)	48
Methyl chloride[3] (CH_2Cl_3)	228
Trichloroethylene (C_2HCl_3)	505

Wastewater treatment plant influent

Material	*Average concentration ($mg\ L^{-1}$)*
Carbon tetrachloride	0.343
Methylene chloride	4.04
Trichloroethylene	3.23

The average influent flow rate to the treatment plant is $0.076\ m^3\ s^{-1}$.

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[1] This example is taken from: Vallero, D. A., and Vesilind, P. A., *Socially Responsible Engineering: Justice in Risk Management*. Wiley, Hoboken, NJ, 2006.

[2] The correct name is tetrachloromethane, but the compound was in such common use throughout the twentieth century and was referred to as carbon tetrachloride that the name is still frequently used in the engineering and environmental professions.

[3] Also known as chloromethane.

Hazardous waste manifests (what leaves the company by truck, headed to a hazardous waste treatment facility)

Material	*Barrels*	*concentration (%)*
Carbon tetrachloride	48	80
Methyl chloride	228	25
Trichloroethylene	505	80

Unused barrels at the end of the year

Material	*Barrels*
Carbon tetrachloride	1
Methyl chloride	8
Trichloroethylene	13

How much VOC is escaping?

Conduct a black box mass balance, as

$$[A_{\underline{acc}}] = [A_{in}] - [A_{out}] + [A_{prod}] - [A_{cons}]$$

where $A_{\underline{acc}}$ = mass of A per unit time accumulated

A_{in} = mass of A per unit time in
A_{out} = mass of A per unit time out
A_{prod} = mass of A per unit time produced
A_{cons} = mass of A per unit time consumed

The materials A are, of course, the three VOC's.

Barrels must be converted to cubic meters and the density of each chemical must be known. Each barrel is $0.12\,\mathrm{m}^2$, and the density of the three chemicals is 1548, 1326, and $1476\,\mathrm{kg\,m}^{-3}$. The mass per year of carbon tetrachloride accumulated is

$$\begin{aligned}[A_{\underline{acc}}] &= 1 \text{ barrel year}^{-1} \times 0.12\,\mathrm{m}^3 \text{ barrel}^{-1} \times 1548\,\mathrm{kg\,m}^{-3} \\ &= 186\,\mathrm{kg\ year}^{-1}\end{aligned}$$

Similarly,

$$[A_{in}] = 48 \times 0.12 \times 1548 = 8916\,\mathrm{kg\ year}^{-1}$$

The mass out is in three parts; mass discharge to the wastewater treatment plant, mass leaving on the trucks to the hazardous waste disposal facility, and the mass volatilizing. So the equation,

$$\begin{gathered}[A_{out}] = [0.343\,\mathrm{g\,m}^{-3} \times 0.076\,\mathrm{m}^3\mathrm{s}^{-1} \times 86\,400\,\mathrm{s\ day}^{-1} \times \\ 365 \text{ day year}^{-1} \times 10^{-3}\mathrm{kg\,g}^{-1}] + [48 \times 0.12 \times 1548 \times 0.80] + A_{air} \\ = 822.1 + 7133 + A_{air}\end{gathered}$$

where A_{air} is the mass per unit time emitted to the air.

Since there is no carbon tetrachloride consumed or produced,

$$186 = 8916 - [822.1 + 7133 + A_{air}] + 0 - 0$$

and

$$A_{air} = 775\,\mathrm{kg\ \ year}^{-1}.$$

If a similar balance is done on the other chemicals, it appears that the losses to air of methyl chloride is about 16 000 kg year^{-1} and the trichloroethylene is about 7800 kg year^{-1}.

If the intent is to cut total VOC emissions, it is clear that the first target should be the methyl chloride, at least in terms of the mass released. But, another important consideration in preventing pollution is *relative risk*.

Although methyl chloride is two orders of magnitude more volatile than the other pollutants, all three compounds are likely to be found in the atmosphere. Thus, inhalation is a likely exposure pathway.

Since risk is the product of exposure times hazard ($R = E \times H$), we can compare the risks by applying a hazard value (e.g. cancer potency). We can use the air emissions calculated above as a reasonable approximation of exposure via the inhalation pathway[4] and the inhalation cancer slope factors to represent the hazard. These slope factors are published by the US EPA and are found to be:

Carbon tetrachloride = 0.053 kg day mg^{-1}
Methyl chloride = 0.0035 kg day mg^{-1}
Trichloroethylene = 0.0063 kg day mg^{-1}

The relative risk for the three compounds can be estimated by removing the units (i.e. we are not actually calculating the risk, only comparing the three compounds against each other, so we do not need units.) If we were calculating risks, the units for exposure would be mass of contaminant per body mass per time, e.g. mg kg^{-1} day^{-1}, whereas the slope factor unit is the inverse of this kg day mg^{-1} so risk itself is a unitless probability:

Carbon tetrachloride = $0.053 \times 775 = 41$
Methyl chloride = $0.0035 \times 16\,000 = 56$
Trichloroethylene = $0.0063 \times 7800 = 49$

Thus, in terms of relative risk, methyl chloride is again the most important target chemical, but the other two a much closer. In fact, given the uncertainties and assumptions, from a relative risk perspective, the importance of the removing the three compounds is nearly identical, owing to the much higher cancer potency of CCl_4. However, it is important to keep in mind that numerous compounds are regulated individually (including several VOCs). Thus, an action plan that addresses overall VOC reductions also needs to ensure that individual compounds do not exceed emission limits.

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[4] Even without calculating the releases, is probably reasonable to assume that the exposures will be similar since the three compounds have high vapor pressures (more likely to be inhaled):

Carbon tetrachloride = 115 mmHg
Methyl chloride = 4300 mmHg
Trichloroethylene = 69 mmHg

After identifying and characterizing the environmental problems, the next step is to discover useful options. These options fall generally into three categories:

1. Operational changes
2. Materials changes
3. Process modifications

Operational changes might consist simply of better housekeeping; plugging up leaks, eliminating spills, etc. A better schedule for cleaning, and segregating the water might similarly yield large return on a minor investment.

Materials changes often involve the substitution of one chemical for another which is less toxic or requires less hazardous materials for clean-up. The use of trivalent chromium (Cr^{3+}) for chrome plating instead of the much more toxic hexavalent chrome has found favor, as has the use of water-soluble dyes and paints. In some instances, ultraviolet radiation has been substituted for biocides in cooling water, resulting in better quality water and no waste cooling water disposal problems. In one North Carolina textile plant, biocides were used in air washes to control algal growth. Periodic "blow down" and cleaning fluids were discharged to the stream but this discharge proved toxic to the stream and the State of North Carolina revoked the plant's discharge permit. The town would not accept the waste into its sewers, rightly arguing that this may have serious adverse effects on its biological wastewater treatment operations. The industry was about to shut down when it decided to try ultraviolet radiation as a disinfectant in its air wash system. Fortunately, they found that the ultraviolet radiation effectively disinfected the cooling water and that the biocide was no longer needed. This not only eliminated the discharge but it eliminated the use of biocides all together, thus saving the company money. The payback was 1.77 years [12].

Process modifications usually involve the greatest investments, and can result in the most rewards. For example, a countercurrent wash water use instead of a once-through batch operation can significantly reduce the amount of wash water needing treatment, but such a change requires pipes, valves and a new process protocol. In industries where materials are dipped into solutions, such as in metal plating, the use of drag out recovery tanks, an intermediate step, has resulted in the savings of the plating solution and reduction in waste generated.

Pollution prevention has the distinct advantage over stack controls that most of the time the company not only eliminates or greatly reduces the release of hazardous materials, but it also saves money. Such savings are in several forms including of course the direct savings in processing costs as with the ultraviolet disinfection example above. The most obvious costs are those normally documented in company records, such as direct labor, raw materials, energy use, capital equipment, site preparation, tie-ins, employee training, and regulatory recordkeeping (e.g. permits) [13]. In addition, there are other savings, including those resulting from not having to spend time on submitting

TABLE 30.2

Pollution Cost Categories

Cost category	Typical cost components
Usual/normal	Direct labor Raw materials Energy and fuel Capital equipment and supplies Site preparation Tie-ins Training Permits: administrative and scientific
Hidden or direct	Monitoring Permitting fees Environmental transformation Environmental impact analyses and assessments Health and safety assessments Service agreements and contracts Legal Control instrumentation Reporting and recordkeeping Quality assurance planning and oversight
Future liabilities	Environmental cleanup, removal and remedial actions Personal injury Health risks and public insults More stringent compliance requirements Inflation
Less tangible	Consumer reaction and loss of investor confidence Employee relations Lines of credit (establishing and extending) Property values Insurance premiums and insurability Greater regulatory oversight (frequency, intensiveness, onus) Penalties Rapport and leverage with regulators

Source: Adapted from Chreremisinoff, N. P., *Handbook of Solid Waste Management and Waste Minimization Technologies*. Butterworth-Heinemann, Burlington, MA, 2003.

compliance permits and suffering potential fines for noncompliance. Future liabilities weigh heavily where hazardous wastes have to be buried or injected. Additionally, there are the intangible benefits of employee relations and safety (see Table 30.2).

VI. MOTIVATIONS FOR PRACTICING GREEN ENGINEERING

In order to understand the reasons why humans behave as they do, one must identify the driving forces that lead to particular activities [14]. The concept of the driving force can also be used to explain engineering processes. For example, in gas transfer the driving force is the difference in concentrations of a particular gas on either side of an interface. We express the rate of this transfer mathematically as ($\mathrm{d}M/\mathrm{d}t = k(\Delta C)$) where M is mass, t is time, k is a proportionality constant, and ΔC is the difference in concentrations on either side of the interface. The rate at which the gas moves across the interface is thus directly proportional to the difference in concentrations. If ΔC approaches zero, the rate drops until no net transfer occurs. The driving force is therefore ΔC, the difference in concentrations.

Analogously in engineering, driving forces spur the adoption of new technologies or practices. The objective here is to understand what these motivational forces are for adopting green engineering practices. We that the three diving forces supporting green engineering seem to be legal considerations, financial considerations, and finally ethical considerations.

A. Legal Considerations

At the simplest and most basic level, green engineering is practiced in order to comply with the law. For example, a supermarket recycles corrugated cardboard because it is the law—either a state law such as in North Carolina or a local ordinance as in Pennsylvania. Engineers and managers comply with the law because of the threat of punishment for noncompliance. So in this situation, managers and engineers choose to do "the right thing," not because it is the right thing to do—but simply because they feel it is their only choice.

History has shown that the vast majority of firms will comply with the law regardless of the financial consequences. It will not even bother to conduct a cost-benefit analysis because it assumes breaking the law is not worth the cost.

Occasionally, however, firms may prioritize financial concerns over legal concerns and the managers may determine that by adopting an illegal practice (or failing to adopt a practice codified in law) they can enhance profitability. In such cases they argue that either the chances of getting caught are low, or that the potential for profit is large enough to override the penalty if they do get caught.

For example, in November 1999 the US Environmental Protection Agency sued seven electric utility companies—American Electric Power (AEP), Cinergy, FirstEnergy, Illinois Power, Southern Indiana Gas & Electric Company, Southern Company, Tampa Electric Company—for violating "the Clean Air Act by making major modifications to many of their coal burning plants without installing the equipment required to control smog, acid rain and soot" [15]. On August 7, 2003, "Judge Edmund Sargus of the US District Court for the Southern District of Ohio found that Ohio Edison, an affiliate of FirstEnergy Corp., violated the Clean Air Act's NSR provisions by undertaking 11 construction projects at one of its coal-fired plants from 1984 to 1998 without obtaining necessary air pollution permits and installing modern pollution controls on the facility" [16]. Given the number of violations, it seems obvious that the companies had calculated that breaking the law and possibly getting caught was the least cost solution and thus behaving illegally was "the right answer."

In some cases private firms can take advantage of loopholes in tax laws that inadvertently allow companies to pretend to be environmentally green while in reality doing nothing but gouging the taxpayer. An example of this is the great synfuel scam [17]. In the 1970s, the US Congress decided to promote the use of cleaner fuels in order to take advantage of both the huge coal reserves in the United States and the environmental benefits derived from burning a clean gaseous fossil fuel made from coal. Producing such synfuel from coal had already been successfully implemented in Canada and the United States Government wanted to encourage our power companies to get into the synfuel business. In order to promote this industry Congress wrote in huge tax credits for companies that would produce synfuel and defined a synfuel as chemically altered coal, anticipating that the conversion would be to a combustible gas that could be used much as natural gas is used today.

Unfortunately, the synfuel industry in the United States did not develop as expected because cheaper natural gas supplies became available. The synfuel tax credit idea remained dormant until the 1990s when a number of corporations (including seemingly unrelated businesses like a hotel chain) found the tax break and went into the synfuel business. Since the only requirement was to change the chemical nature of the fuel, it became evident that even spraying the coal with diesel oil or pine tar would alter the fuel chemistry and that this fuel would then be legally classified as a synfuel. The product of these synfuel plants was still coal, and more expensive coal than raw coal at that, but the tax credits were enormous. Companies formed specifically to take advantage of the tax break, often with environmentally attractive names like Earthco, and made huge profits by selling their tax credits to other corporations that needed them. The synfuels industry presently is receiving a gift from the US taxpayer of over $1 billion annually, while doing nothing illegal, but also while doing nothing to benefit the environment.

B. Financial Considerations

Decisions about the adoption of green practices are also driven by financial concerns. This level of involvement with "greening" is at the level promoted by the economist Milton Friedman, who stated famously, "The one and only social responsibility of business [is] to use its resources and engage in activities designed to increase its profits so long as it ... engages in open and free competition, without deception or fraud" [18]. In line with this stance, the firm calculates the financial costs and benefits of adopting a particular practice and makes its decision based on whether the benefits outweigh the costs or vice versa.

Many companies seek out green engineering opportunities solely on the basis of their providing a means of lowering expenses, thereby increasing profitability. Here are some examples [19]:

- In one of its facilities at Deepwater, New Jersey, Dupont uses phosgene, an extremely hazardous gas, and used to ship the gas to the plant. In an effort to reduce the chance of accidents, DuPont redesigned the plant to produce phosgene on site and to use almost all of it in the manufacturing process, avoiding and costs associated with hazardous gas transport and disposal.
- Polaroid did a study of all of the materials it used in manufacturing and grouped them into five categories based on risk and toxicity. Managers are encouraged to alter product lines in order to reduce the amount of material in the most toxic groups. In the first five years, the program resulted in a reduction of 37% of the most toxic chemicals, and saved over $19 million in money not spent on waste disposal.
- Dow Chemical challenged its subsidiaries in Louisiana to reduce energy use, and sought ideas on how this should be done. Following up on the best ideas, Dow invested $1.7 million, and received a 173% return on its investment.

Other firms may believe that adopting a particular green engineering technology will provide them with public relations opportunities: green engineering is a useful tool for enhancing the company's reputation and community standing. If the result is likely to be an increase in sales for the business, and if sales are projected to rise *more* than expenses, so that profits rise, the firm is likely to adopt such a technology. The same is true if the public relations opportunities can be exploited to provide the firm with expense reductions, such as decreased enforcement penalties or tax liabilities. Similarly, green technologies that not only yield increased sales, but also at the same time decrease expenses are the perfect recipes for the adoption of green practices by a company whose primary driving forces are financial concerns. For instance:

- Dupont's well-publicized decision to discontinue its $750 million a year business producing CFCs was a public relations bonanza. Not only did DuPont make it politically possible for the United States to become a signatory to the Montreal Protocol on ozone depletion, but it already had alternative refrigerants in the production stage and were able to smoothly transition to these. In 1990, the US Environmental Protection Agency gave DuPont the Stratospheric Protection Award in recognition of their decision to get out of CFC manufacturing [20].
- The seven electric companies sued by the EPA in November 1999 for Clean Air Act violations heavily publicized their efforts to reduce greenhouse gas emissions. For example, AEP issued news releases on May 8, June 11, and November 21, 2002 regarding emissions reduction efforts at various plants.

These examples clearly demonstrate bottom-line thinking: cases in which managers were simply trying to practice "good business," seeking ways to increase the difference between revenues and expenses so that profits would rise. These decisions apparently were not influenced by the desire to "do the right thing" for the environment. Businesses are organized around the idea that they will either make money or cease to survive; in the "financial concerns" illustrations so far provided, green practices were adopted as a means of making more money.

On occasion, though, managers are *forced* into considering the adoption of greener practices by the threat that not doing so will cause expenses to rise and/or revenues to fall. For example, in October 1998, Earth Liberation Front (ELF)) targeted Vail Ski Resort, burning a $12 million expansion project to the ground [21]. In the wake of this damage, the National Ski Areas Association (NSAA) began developing its Environmental Charter in 1999 with "input from stakeholders, including ... environmental groups" [22] and officially adopted the charter in June 2000 [23]. In accordance with the charter, NSAA has produced its Sustainable Slopes Annual Report each year since 2001 [24]. NSAA was spurred to create the Environmental Charter by concerns about member companies' bottom lines: further "ecoterrorist" activity could occur, thereby causing expenses to rise; and the ELF action may have sufficiently highlighted the environmental consequences of resort development to the point that environmentally minded skiers might pause before deciding to patronize resorts where development was occurring, thereby causing revenues to fall.

Similarly, for firms trying to do business in Europe, adopting ISO 14000 (environmental management) is close to a required management practice. The ISO network has penetrated so deeply into business practices that firms are nearly locked out if they do not gain ISO 14000 certification.

There is ample evidence that one of the reasons businesses participate in the quest for sustainability is because it is good for business. The leaders of eight leading firms that adopted an environmentally proactive stance on sustainability were asked in one study to justify the firms' adoption of such a strategy [25]. All companies reported that they were motivated first by regulations such as the control of air emissions, pretreatment of wastewater, and the disposal of hazardous materials. One engineer in the study admitted that: "The [waste disposal] requirements became so onerous that many firms recognized that benefits of altering their production processes to generate less waste."

The second motivator identified in this study was competitive advantage. Lawrence and Morell quote one director of a microprocessor company, who noted that "by reducing pollution, we can cut costs and improve our operating efficiencies." The company recognized the advantage of cutting costs by reducing its hazardous waste stream [26].

Another study, conducted by PriceWaterhouseCoopers, confirmed these findings [27]. When companies were asked to self-report on their stance on sustainable principles, the top two reasons for adopting sustainable development were found to be:

1. enhanced reputation (90%),
2. competitive advantage (cost savings) (75%).

It is not clear if the respondents were given the option of responding that they practiced sustainable operations because this was mandated by law. If it had, there is no doubt that all companies would have publicly stated that they are, indeed, law abiding.

So it seems likely that the two primary driving forces behind the adoption of green business and engineering practices are (1) legal concerns and (2) financial concerns. According to Sethi [28], one can argue instead that actions undertaken in response to legal and financial concerns are actually *obligatory*, in that society essentially demands that businesses make their decisions within legal and financial constraints. For an action to be morally admirable, however, the motivation has to be far different in character.

C. Ethical Considerations

The first indication that some engineers and business leaders are making decisions where the driving force may not be due to legal or financial concerns comes from several cases in American business. Although most business or engineering decisions are made on the basis of legal or financial concerns, some companies believe that behaving more environmentally responsible is simply the right thing to do. They believe that saving resources for the generations that will follow is an important part of their job. When making decisions, they are guided by the "triple bottom line." Their goal is to balance the financial, social, and environmental impacts of each decision.

A prime example of this sort of thinking is the case of Interface Carpet Company [29]. Founded in 1973, its founder and CEO until 2001 was Ray Anderson, now Chairman of the Board. By the mid-1990s, Interface had grown to nearly $1.3 billion in sales, employed some 6600 people, manufactured on four continents, and sold its products in over 100 countries worldwide. In 1994, several members of Interface's research group asked Anderson to give a kick-off speech for a task force meeting on sustainability: they wanted him to provide Interface's environmental vision. Despite his reluctance to do so—Anderson had no "environmental vision" for the company except to comply with the law—he agreed. Fortuitously, as Anderson struggled to determine what to say, someone sent him a copy of Paul Hawken's *The Ecology of Commerce* [30]; Anderson read it, and it completely changed not only his view of the natural environment, not only his vision for Interface Carpet Company, but also his entire conception of business. In the coming years, he held meetings with employees throughout the Interface organization explaining to them his desire to see the company spearhead a sustainability revolution. No longer would they be content to keep pollutant emissions at or below regulatory levels: Instead, they were going to strive to be a company that created zero waste and did not emit any pollutants *at all*. The company began to employ "The Natural Step" [31] and notions of "Natural Capitalism" [32] as part of its efforts to become truly sustainable. The program continues today, and although the company has saved many millions of dollars as a result of adopting green engineering technologies and practices, the reason for adopting these principles was not to earn more money but rather to do the right thing.

Yet another example is that of Herman Miller, an office furniture manufacturing company located in western Michigan. Its pledge in 1993 to stop sending any materials to landfills by 2003 has resulted in the company's adoption of numerous progressive, but sometimes expensive, practices. For example, the company ceased taking scrap fabric to the landfill and began shredding it and trucking it to a firm in North Carolina that processes it into automobile insulation. This environmentally friendly process costs Herman Miller $50 000 each year, but the company leaders agree that a decision that is right for the environment is the right decision. Similarly, the company's new waste-to-energy plant has increased costs, but again company leaders feel it is worth the cost, as employees and managers are proud of the company's leadership in preserving the natural environment in their state [33].

The decisions made by the leadership of Interface Carpet Company and Herman Miller were not morally admirable simply because they enabled these companies to reduce toxic emissions (among many other positive outcomes for the environment); they were morally admirable because the *driving force* behind those decisions was the desire to protect it the environment so that future generations would be able to enjoy it as much as, or even more than, we do today. Conversely, in the cases of Dupont, Polaroid, and Dow Chemical cited earlier, the *driving force* behind their decisions to adopt green technologies was appeared to be a desire to save the company money; the benefits to the Earth were simply a fortunate byproduct of those decisions.

VII. FUTURE PEOPLE

One of the unique characteristics of humans is that we have self-awareness. We can see ourselves in the world today, and we know that humans existed in days gone by, and our species will (we hope) exist tomorrow. We thus are able to plan for the future and accept delayed gratification.

But there will come a time in the future where we individually are long dead and we can no longer personally benefit from any actions we might have taken on our own behalf. Or, for that matter, there will come a time, after our death, when we are not longer burdened by the ill-considered actions that might have led to unhappiness. Why, then worry about the future?

We can, based on empirical evidence, assume that there will be a future, of some sort, and we have some confidence that this future will be inhabited by human beings. It is this future—the future without you and me, that we now address.

While the "client" for engineers is almost always an existing person or organization, the work in which engineers engage can have far-reaching consequences for persons who are not yet even born, or future people. It is easy to argue that engineers have a moral responsibility by virtue of their position in society to existing people, but does this extend as well to these future persons, those as yet unborn, who may or may not even exist?

We believe there are two reasons why the engineer has moral responsibilities to future people:

- Many engineering works, be they small gadgets or huge buildings, will certainly last for more than one generation and will be used by people who were not yet born when the product or facility was constructed.
- Engineers can and do appreciably alter the environment, and the health, safety, and welfare of future people will depend on maintaining a sustainable environment.

Engineers conceive, design, and construct products and facilities that last for generations. Indeed, many engineering decisions have no effects until decades later. For example, suppose engineers choose to dispose of some hazardous waste in steel containers buried underground. It may take generations for waste containers to corrode, for their contents to leach, for the leachate to migrate and pollute groundwater, and for toxic effects to occur in people coming in contact with the water. Such a problem is not of concern for present people since it will be decades before the effects are felt. The only persons to be adversely affected by such an engineering decision are future people, and they are the only ones who have no say in the decision.

Some would argue that we owe no moral obligations to future generations because they do not exist and the alleged obligation has no basis because we do not form a moral community with them. This is a fallacious argument, however. Even if future generations do not yet exist (by definition); we can still have obligations to them. If we agree that we have moral obligations to distant peoples who we do not know, then it would be reasonable to argue that we have similar moral obligations to people who are yet unborn.

Vesilind and Gunn [34] use an analogy to illustrate this point. Consider a terrorist who plants a bomb in a primary school. Plainly the act is wrong, and in breach of a general obligation not to cause (or recklessly risk) harm to fellow citizens. Even though the terrorist may not know the identities of the children we would all agree that this is an evil act. And the same would be true if the terrorist bomb had a very long fuse, say 20 years. This would be equally heinous, even though the children, at the time the bomb was placed, had yet not been born. Some engineering works, such as the hazardous waste disposal alluded to above, have very long fuses, and there is no doubt that future people can be harmed by irresponsible engineering activities. The act of burying wastes in the ground where they will not find their way to drinking water supplies for some decades is no different from the act pouring the wastes down a well, except in terms of time.

The second way that engineers have responsibility to future generations is by consciously working to maintain a sustaining environment. Global warming is one instance where the damage done to date is so severe that the effects will not be felt until many years from now. Most models predict that by building up greenhouse gasses at the present time, the temperature of the earth will be slowly getting warmer even if and when we begin to reduce the emission of such gases. This is analogous to heating a pot of water on an electric stove. The burner is turned on and the water begins to heat. When the burner is turned off the temperature of the water does not drop immediately to room temperature. The burner is still warm and heat continues to be transmitted to the pot and the temperature of the water continues to rise even after the burner is turned off. This effect will also occur with global warming (although rather than heat being buffered, the decrease in the concentrations of greenhouse gases will resist change even after the sources are removed). We therefore may have already exceeded the level of sustainability with regard to the earth's temperature but we will not know about it until decades from now [35].

Some argue that we have no obligation to maintain a quality environment for future generations because we cannot know what kind of an environment they will want. Our sole responsibility to future generations is therefore not to plan for them [36].

We know very well that future generations will *not* want contaminated air or water, dramatically reduced number of species, or global warming. Certainly there will be changes in style and fashion, and future generations will no doubt have different views on many of our present moral issues, but they will want a sustainable environment for themselves and their children. Irreparable global warming, or large-scale radiation, or the destruction of the ozone layer are not, under any circumstances, what our progeny would want. Parents do not know what careers their children will choose when they grow up, whom they will marry, or what their life style will be like, but the parents *do* know that their children will want to be healthy, and thus the parents are morally obligated to provide heath care for their children. Also, future generations most likely will not want to suffer genetic damage or to produce babies with severe birth defects, and thus our obligation to them is to control chemical pollution. The argument that because we do not know the desires of future people our only obligation is to not plan for them is therefore wrong.

The engineers' responsibilities to society are the control and prevention of pollution, and they are therefore entrusted to help maintain a healthy environment. Because this responsibility extends into the future, the "public" in the first canon in the codes of ethics should refer to all people, present and future.

Future, therefore, is the future beyond the careers of present engineers. But unlike some laborers or trades-people, the effect of their work will last long after then are no longer around. Is it important to you, today, to know that what you do will have a positive effect on future people?

The profession and practice of engineering is changing, but we will always be required to have strong analytical skills. The engineer of the future will increasingly need "practical ingenuity," as well as the ability to find new ways of doing things (i.e. creativity) built on a framework of high ethical standards, professionalism, and lifelong learning [37]. These are the qualities of a *good* engineer.

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9. Since we brought it up, the SIDS Alliance recommends a number of risk reduction measures that should be taken to protect infants from SIDS:

    - *Place your baby on his or her back to sleep*: The American Academy of Pediatrics recommends that healthy infants sleep on their backs or sides to reduce the risk for SIDS. This is considered to be most important during the first six months of age, when baby's risk of SIDS is greatest.
    - *Stop smoking around the baby*: SIDS is long associated with women who smoke during pregnancy. A new study at Duke University warns against use of nicotine patches during pregnancy as well. Findings from the National Center for Health Statistics now demonstrate that women who quit smoking during pregnancy, but resume after delivery, put their babies at risk for SIDS, too.
    - *Use firm bedding materials*: The US Consumer Product Safety Commission has issued a series of advisories for parents regarding hazards posed to infants sleeping on top of beanbag cushions, sheepskins, sofa cushions, adult pillows, and fluffy comforters. Waterbeds have also been identified as unsafe sleep surfaces for infants. Parents are advised to use a firm, flat mattress in a safety-approved crib for their baby's sleep.

- *Avoid overheating, especially when your baby is ill*: SIDS is associated with the presence of colds and infections, although colds are not more common among babies who die of SIDS than babies in general. Now, research findings indicate that overheating too much clothing, too heavy bedding, and too warm a room may greatly increase the risk of SIDS for a baby who is ill.
- *If possible, breastfeed*: Studies by the National Institute of Health show that babies who died of SIDS were less likely to be breastfed. In fact, a more recent study at the University of California, San Diego found breast milk to be protective against SIDS among nonsmokers but not among smokers. Parents should be advised to provide nicotine-free breast milk, if breastfeeding, and to stop smoking around your baby particularly while breastfeeding.
- *Mother and baby need care*: Maintaining good prenatal care and constant communication with your health care professional about changes in your baby's behavior and health are of the utmost importance.

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QUESTIONS

1. Consider the black box balance example. Calculate the amount of vapors escaping from 500 barrels of carbon tetrachloride (85%), with 10 barrels remaining; 1000 barrels of methyl chloride (30%) with 100 barrels remaining; and, 2000 barrels of TCE (85%) with 200 barrels

remaining. Which of the three VOCs presents the greatest risks? What are the relative risks of from the three compounds?

2. Consider a facility in your hometown. What three steps could be taken in the life cycle to improve air pollution emissions?
3. Give an example of a company in your home state that has turned an environmental problem into a profit. What were the major drivers? What were the obstacles that had to be overcome?