Solid Waste: Assessment, Monitoring and Remediation
Twardowska, Allen, Kettrup and Lacy (Editors)

VI.3

Thermal waste treatment – a necessary element for sustainable waste management

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VI.3.1. Introduction

This chapter focuses on the role of thermal waste treatment within waste management as a whole. First, it is shown that the amount and composition of wastes are changing due to the changing pattern of consumption. Second, the goals of waste management are introduced, and means to reach these goals are discussed. It is concluded that even if many waste materials are recycled, there are plenty of wastes that have to be disposed of. Third, the most common thermal waste treatment processes (including co-firing) are presented.

Priority is given to understand that municipal solid waste (MSW) incineration is an important process for environmental protection and resource recovery. The goals of incineration are discussed, and detailed examples are given to show how these goals can be reached. Also, deficiencies and routes for further improvement of incineration technology are pointed out.

The chapter is brought to a close by an example of how MSW incinerators are actually used to routinely analyze the composition of MSW in a cost-effective and continuous way.

VI.3.2. Materials consumption, goals of waste management and incineration

VI.3.2.1. Phenomena of modern anthropogenic metabolism

In order to optimize waste management, the so-called "Metabolism of the Anthroposphere" has to be understood: input and output of man-made systems are related to each other, waste generation is a function of production and consumption processes. Hence, it is essential to look first at the most important phenomena of today's metabolism (Brunner and Rechberger, 2001).

1. Since prehistoric times, the turnover of materials has increased dramatically. This is not only due to population increase, but also mainly due to the enormous technological and economic advancements in the last few centuries. Today, modern man consumes in his household more than 80 t per capita and year (Baccini and Brunner, 1991). If the material flows in the hinterland and the so-called rucksacks are included, this amount is easily doubled (Schmidt-Bleek, 2000). The mining and consumption of many individual substances such as lead has grown even more (Fig. VI.3.1): since the first industrial use

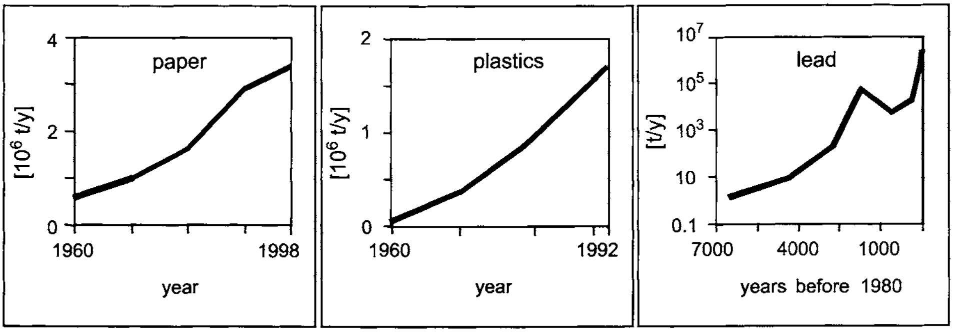

Figure VI.3.1. The rates of material consumption are high and growing. All these materials have to be recycled or disposed off by waste management. Figures for paper and plastics are from Austria, figures for lead are global production figures according to Settle and Patterson (1980).

of lead, there has been a 10 million-fold increase in the utilization of this mineral. This is the case for other substances too. The main material turnover is the water used for the transportation of dirt (toilet, personal hygiene, laundering and dish washing). Second comes air for the oxidation of fuel for heating/cooling and transportation. Third are construction materials and fuel. The large input implies a large and unprecedented output of sewage, off gas and solid wastes.

There are no indications yet that material growth will come to an end. Both per capita consumption rate as well as population rate increase, and thus for most regions on the globe, the material turnover is increasing. Figure VI.3.1 clearly illustrates the growth: in the past 30–40 years, the production of paper has grown by a factor of five; plastic consumption has risen by more than an order of magnitude. Due to the high increase in consumption, the mass of wastes generated is also large and growing. For goods with long residence times, huge amounts of wastes will arrive in the future. Hence, the main challenge for waste management is to come: future amounts and compositions of wastes are much different than today's wastes and they cannot be avoided by prevention because they already exist today in the stocks (see below). Prevention strategies can only be successful if they take into account, production and consumption. They have to be directed towards a reduction of the material input into the anthroposphere, as well as the prolongation of the residence (= utilization) time.

2. Due to the large consumption rate, some anthropogenic flows are surpassing natural flows of erosion and weathering. This means that concentrations in certain environmental compartments become dominated by man-made impacts. Nature will have to adapt to these new anthropogenic conditions. If changes induced by man are too fast, environmental problems can arise. It may be hypothesized that the limits to growth are not at the supply side of the system: resources are still abundant for long time periods. But at the backend of the material flow system, new limits become visible: the anthropogenic metabolism seems to be limited by the availability of final sinks for material disposal. A first example was given by halogenated hydrocarbons (chlorinated and fluorinated hydrocarbons (CFCs)) that diminished the stratospheric ozone layer. While the production of CFCs is not bound to any resource limitations at this moment, the efficient collection and disposal of these chemicals is a problem not solved yet, and thus they have been

banned from being produced. A next and still controversial example is carbon: while the resources of coal will still last for a couple of centuries, the products of the utilization of coal, namely CO_2, contribute to the greenhouse effect. Experts predict global warming to an unacceptable level if the consumption of coal continues to grow at the present growth rates. Other examples are nutrients: in countries such as the Netherlands, the main problem is not how to get the resource nitrogen, but how to get rid of it. Groundwater concentrations are high and rising due to high imports of nutrients for agricultural purposes not paralleled by corresponding exports.

3. The input of materials into most urban regions is larger than the output, resulting in an increase of stock within the anthroposphere, in particular in cities. Figure VI.3.2 demonstrates this for plastic materials in Austria. There are two stocks of plastics: first, the materials stored in "consumption", e.g. in products with long residence times such as construction materials, floor linings, car parts, etc. and second, the stock in landfills. Of the two stocks, landfill is more important. The stocks can serve as future resources, but is also a future threat to the environment.

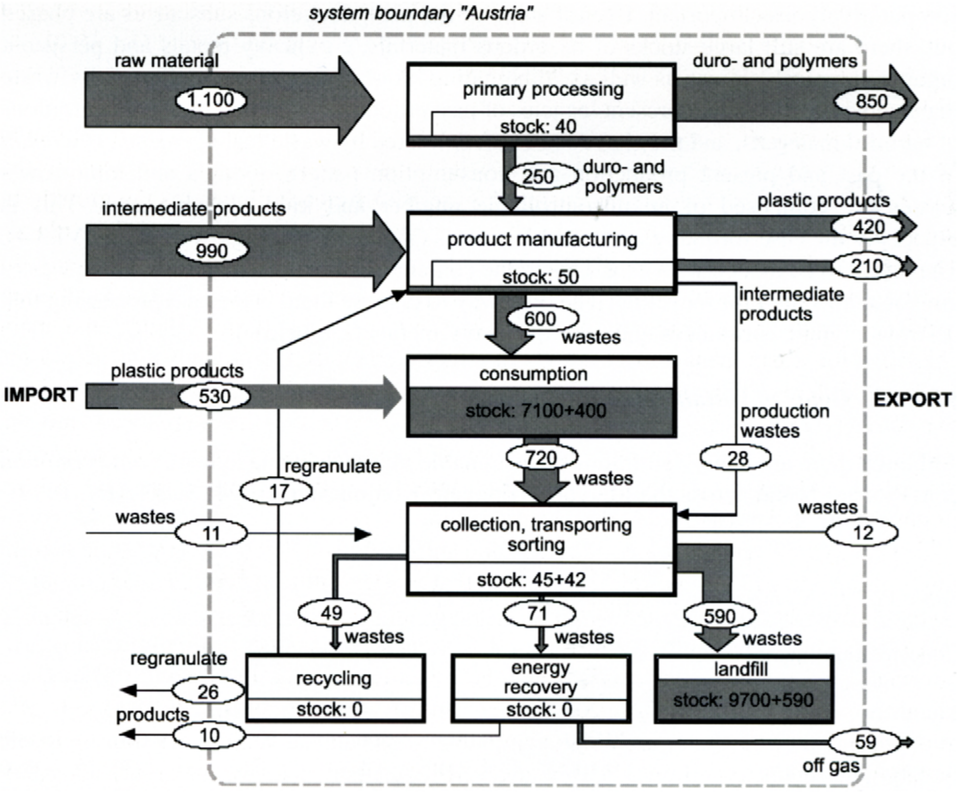

Figure VI.3.2. Inputs of materials into regions are generally larger than outputs, resulting in huge stocks of materials that have to be managed in the future. The figure on flows of plastic materials in Austria [in kt/y for 1994] shows that the growth rates of the stocks of plastic are high, and that large amounts of valuable resources (energy!) are disposed off in landfills (Fehringer and Brunner, 1997).

4. The flow of materials through the anthroposphere is mainly linear; there are hardly any cycles yet. The task to recycle materials at a considerable amount within an urban region is very challenging. It is doubtful if a significant fraction can be recycled within the next 25 years. In any case, it would mean a completely new management of materials within this time span.

5. In advanced societies, and due to pollution prevention measures, the emissions from consumption are larger than the emissions from production. This implies new priorities in environmental management. The new focus must be on non-point, consumer-oriented sources. Since the number of consumers is more than the producers, it is more difficult to reduce emission flows from consumer sources. For producers, it is "easier" to add pollution abatement equipment to their facilities than to design and introduce new low-emission consumer products. For example, in earlier days the process of galvanization was a major source for heavy metals in the environment. Today it is the use of corrosion-resistant consumer goods such as zinc-coated surfaces that are most important as emission sources.

The significance of these phenomena of modern metabolism for waste management is the following: as the amount of consumer waste increases, industrial wastes become comparatively less important. Even if some of the most dangerous substances are phased out, there are still large stocks of hazardous materials, e.g. heavy metals and persistent organic chemicals, in use as well as "hibernating" (out of use but not collected by waste management yet). They represent legacies of past products containing high concentrations of harmful materials, and they have to be safely treated by waste management. As a result of the past and present production and consumption pattern, today's and tomorrow's wastes are composed of an uncontrollable number and kind of substances. This is especially the case for many combustible wastes (Table VI.3.1, Figs. VI.3.3 and VI.3.4). They have to be treated with care. Due to the content of hazardous materials, some wastes are not at all suited for recycling. The only way to dispose them is thermal processing that destroys organic substances and controls heavy metals (see below).

VI.3.1.2. Goals of sustainable waste management

Although there are many definitions of sustainable materials management, some common concepts are found across the literature (Enquete-Kommission, 1994; SUSTAIN, 1994).

Table VI.3.1. Composition of combustible wastes in Austria.

Concentration (mg/kg d.m.)	N	Cl	Cd	Hg	Pb	Zn
Minimum	200	10	0.01	0.001	<1	1
Maximum	670,000	480,000	500	10	4,000	16,000
Average of all waste	9,100	4,300	5.7	0.8	230	520
MSW	7,000	8,700	10	2	800	1,100

There is a large variety in the content of metals and non-metals; while some wastes are well suited to be used in thermal processes with little APC such as cement kilns, others can only be treated in incinerators with the most advanced control equipment.

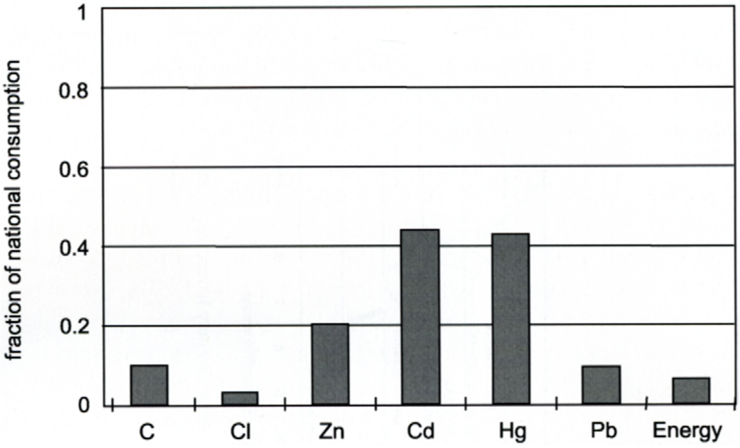

Figure VI.3.3. Relative flow of materials and energy in combustible wastes in Austria: while the contribution of all wastes to the national energy balance of Austria is small (< 10%), more than 40% of the national import of cadmium and mercury is found in combustible wastes. Thus, priority in thermal treatment has to be put first on safe material handling, and only second on maximum energy recovery.

- *Conservation of renewable resources*: The present use of renewable substances should not reduce the capital stock of future generations.
- *Sustainable emissions*: Material flows from the anthroposphere[1] to the environment should neither exceed local and global assimilation capacity nor surpass the range of natural material flows.
- *Change in stocks of materials*: Material flows should be managed in a way to prevent the depletion of useful and the accumulation of harmful materials in the environment.

In the context of the above principles, the main tasks of waste management are twofold: first, waste treatment acts as one of the main interfaces between the anthroposphere and the environment, ensuring that material flows across this boundary have an acceptable impact on the environment. Second, waste management is a key element in conserving material and energy by recycling. The two goals, "protection of men and the environment" and "conservation of resources", have been introduced in the legislation on waste management of many countries. In addition, based on the precautionary principle, which is also a major principle of sustainable development, some nations such as Austria, Germany and Switzerland are aiming at landfills, which do not require after-care measures. This strategy calls for extensive waste pretreatment before landfilling.

Environmental protection and resource conservation are goals not only for waste management, but also for all activities of a sustainable economy. It is thus important to compare the costs to accomplish these goals by means of waste management with other measures such as pollution prevention and air or water pollution control in the production and consumption sector. In this respect, it is important to note that the ratio of consumption emissions versus production emissions is constantly rising. Also, some of the new and

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[1] The *anthroposphere* is the sphere where human activities take place, comprising all man-made sources, sinks, processes, flows and stocks of goods and substances.

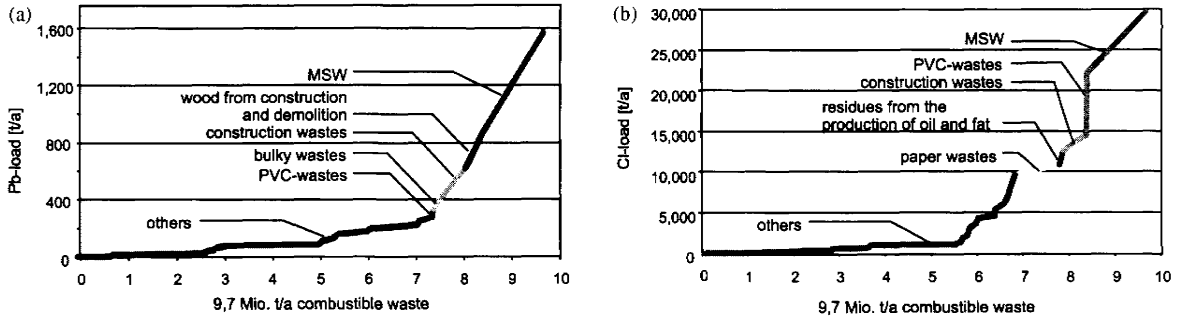

Figure VI.3.4. Load of materials (a: lead, b: chlorine) in combustible wastes in Austria: MSW is the most important carrier of many hazardous material.

growing consumption emissions, such as the loss of metals from surface coatings during a life cycle, take place outside the range of the classical measures of waste management and pollution control.

As stated above, the first objective of waste management is the protection of man and the environment. In the past, this meant to prevent hygienic risks by organizing the proper collection and disposal of wastes. Today, these risks have been minimized in advanced countries. Keeping the goals of sustainable materials management in mind, the new challenge stems from the large amounts of materials that are being consumed by modern societies. Waste management must be able to handle this large amount, recycle or dispose it in a manner that observes environmental quality standards. In particular, waste management must find for all non-recyclable materials *appropriate final sinks*, such as landfills, soils or sediments. Since the material flows have increased tremendously in the past century, this task cannot be fulfilled by uncontrolled dispersal of materials in water, air or soil.

The main challenge for waste management does not arise from the *bulk properties* of the waste itself, such as MSW, construction wastes or sewage sludge. The real assets and hazards are the very *substances* contained in these wastes. This is demonstrated by the following examples. (1) Due to the fact that MSW contains the *substances* carbon and hydrogen, it is well suited for incineration and energy recovery. However, due to the small amounts of substances such as mercury and cadmium, incinerators utilizing MSW must be equipped with highly efficient air pollution control (APC) devices. (2) It is the content of nutrients and humic substances, which makes sewage sludge attractive for land application. On the other hand, there are severe restrictions for the application of sewage sludge in agriculture because of small amounts of organic and inorganic trace substances in sludge such as heavy metals, PCBs and dioxins. (3) The reuse of certain plastic materials is challenged by the presence of traces of hazardous substances used as stabilizers. (4) The potential of waste biomass to be turned into useful compost is again limited by an array of refractory and harmful trace substances.

These examples show that *substances* contained in waste materials are important to consider when decisions in waste management are taken. In order to reach the goals of wastes and material management, the fate of the important matrix and trace substances contained in wastes has to be known. Substances have to be actively managed and directed to appropriate anthropogenic or natural "conveyor belts", such as recycling goods or water and air. The power of a waste treatment process to concentrate or dilute substances must be taken into account. In every case, it must be considered that ultimately, a final sink has to be found for all substances contained in all goods. Decisions regarding the management of wastes have to be based on sufficient information about the fate of materials in waste treatment processes. Up to now, such comprehensive sets of information are abundantly available for MSW incineration, and lacking for many other waste treatments.

The means to reach the goals of waste management are prevention, recycling and disposal. It is important to note that prevention and recycling *per se* are not goals, but they can be efficient instruments to fulfill the goals. In general, a decision about the choice of any of the three means should be based on the goals to be fulfilled and the costs of the measures to reach the specified goals. Thus, the three means are competing with each other for overall efficiency in environmental protection and resource recovery. From science and technology, as well as economy point of view, an *a priori* preference for prevention, recycling or disposal is hard to justify. It is noteworthy that under certain boundary conditions, recycling of a material may be a less favorable scenario when compared to the linear disposal option.

In general, waste management in view of the sustainable materials management means to choose one of the following options or combinations thereof:

1. recycling of material and energy with acceptable emissions, including treatment and disposal of the recycling good after *x* cycles (e.g. plastic materials, cellulose);
2. dilution of waste materials by water, soil and air to environmentally acceptable levels (e.g. biochemical or thermal degradation of biomass resulting in dilution of CO_2 and chlorides in air and surface water);
3. treatment and storage in a final sink, namely in a storage with a very long residence time and small long-term emissions below environmental standards (e.g. storage of MSW filter ash in underground salt mines or immobilized MSW bottom ash in mono fills).

In summary, there are large amounts of potentially hazardous substances in waste materials, many of which will be encountered in ordinary MSW. There is a high uncertainty about the distribution of the substance concentrations in wastes. Therefore, it is important that waste treatment processes are able to cope with a very wide array of substances and in a sufficiently broad concentration range, including peak loads. Safe, goal-oriented treatment processes are required, which will direct both the organic and the inorganic substances to the appropriate recycling processes and sinks. For many organic substances, this means complete transformation by thermal processes to CO_2, water and other mineralized end products. For inorganic substances, either recycling as a mineral or immobilization and disposal in a final storage landfills is required.

VI.3.3. Thermal processes used for waste treatment

Thermal processes for waste treatment can be divided into the actual combustion process and the following steps necessary for air and water pollution control. The choice for the combustion technology is mainly determined by the physical (particle size distribution, density, aggregate state, water content, etc.) and chemical (elemental composition, calorific value, ash content, etc.) characteristics of the waste. MSW as an example for a heterogeneous feed is often incinerated in the so-called mass-burn facilities (Fig. VI.3.5).

Waste is stored in a fully contained waste bunker for time periods up to 1 week. Combustion air is taken from the bunker thus preventing odor outside the facility. An automatic or man-controlled crane mixes incoming wastes to increase homogeneity (especially with regard to calorific value), and lifts the waste via a feeding hopper in a water-cooled gravity chute, which serves as an air seal between the bunker and furnace. Usually a hydraulic or mechanical ram system expels the waste from the chute onto the furnace grate where the actual combustion process takes place. The grate consists of moving and fixed elements (rows) that guarantee controlled transportation, mixing of the waste and equal distribution across the grate. Several grate designs exist (reciprocating grate, drum grate, traveling grate, etc.). Part of the combustion air is injected as primary combustion air from underneath through the grate (underfire air). This provides cooling for the grate material to prevent heat damage and excessive oxidation. In addition, the waste is

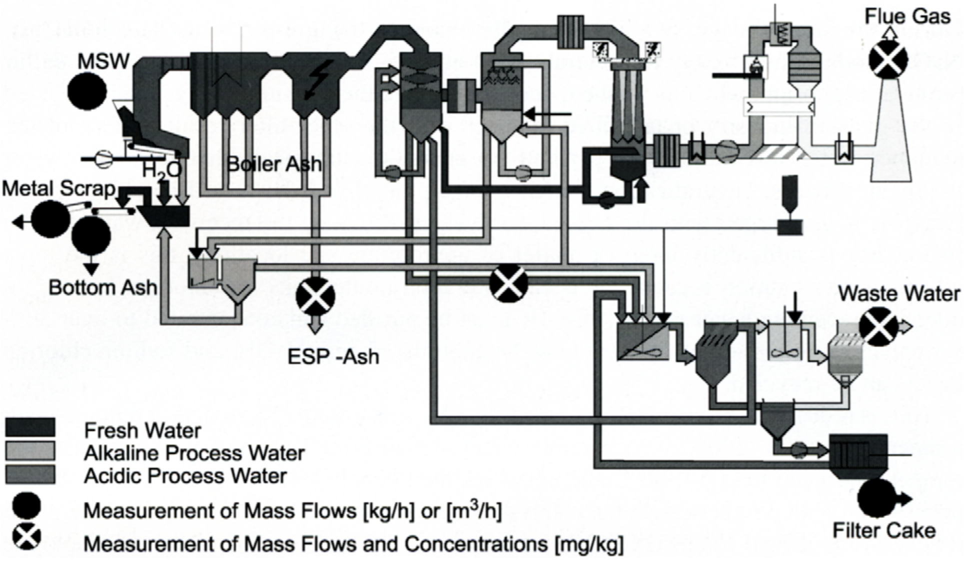

Figure VI.3.5. Modern MSW incinerator with state-of-the-art APC device. The incinerator shown treats 34 t/h of MSW resulting in 9.2 t/h bottom ash, 1.1 t/h scrap metals, 0.97 t/h filter-ash, 14 t/y wastewater, 0.055 t/h filter cake, 230 t/h flue gas. Indicated are measuring points for routine measurements of waste composition according to the method described in Chapter VI.3.3: iron is determined in metal scrap, mercury in acid scrubber discharge, chlorine in treated wastewater, carbon in cleaned flue gas and lead, cadmium, copper and zinc in ESP ash.

well mixed with air, a requirement for complete mineralization of all organic carbon. Secondary combustion air (overfire air) is injected into the combustion chamber above the grate to guarantee maximum oxidation of all organic compounds (carbon and tar particles, hydrocarbon vapors, etc.) and low CO concentrations in the flue gas. At the end of the grate, the mineralized bottom ash is discharged into a water basin, where it is cooled and removed to the bottom ash bunker. The water basin acts as a seal for the furnace.

The flue gas after the combustion chamber contains high amounts of particulates (3–5 g/m^3), acids such as SO_2 (sulfur dioxide), HCl (hydrochloric acid), HF (hydrofluoric acid), and NO_x (nitrogen oxides), which require extensive flue gas treatment. Particulates are either removed in electrostatic precipitators (ESP) or bag house filters (also referred to as fabric filters). ESPs use electric forces to charge and move particulate matter in a flowing gas stream to a collecting surface. They are more robust towards temperature changes, have lower pressure drops and are easy to maintain. Bag house filters (particulate removal by filtration on fiber surfaces) achieve high removal efficiencies for fine particles (<5 μm, $>99.9\%$). Additionally, they can be employed in combination with pollutant-adsorbing substances (e.g. activated carbon to remove mercury and dioxins; $CaCO_3$ (limestone), CaO (lime), $Ca(OH)_2$ (hydrate lime) or a mixture of it to remove acids) that are injected into the flue gas up-stream (spray dryer absorber) and collected in the filter device. Acids can be very efficiently and separately removed by a two-stage wet scrubber system. HCl and HF are physically absorbed in the first acid scrubber stage at $pH \approx 1$. The low pH prevents absorption of SO_2. The scrubber liquid is water, and no neutralization agent has to be used. Also, mercury-chlorides are removed from the flue gas at this stage.

During the second stage, SO_2 is chemically absorbed using either $CaCO_3$, $Ca(OH)_2$ or NaOH (sodium hydroxide) for neutralization at pH ≈ 7. The final product of the sulfur removal is gypsum, which is washed, dewatered and either (if sufficiently clean) recycled in the gypsum industry or landfilled together with the other filter residues. Part of the scrubber water is continuously purified by an on-site physical–chemical wastewater treatment process. Neutralization sludge is precipitated and dewatered in a filter press. Chloride is discharged with the treated wastewater. Provided the receiving water for the incinerator is sufficiently large (a matter of appropriate site location), this is the most advantageous solution because the oceans are appropriate sinks for chloride. In case no adequate receiving water is available, HCl can be purified and concentrated to over 30% for recycling. Alternatively, the acid can be neutralized with NaOH, and sodium chloride brine can be recycled.

NO_x is reduced to N_2 and H_2O by injecting NH_3 (ammonia). The reaction requires high temperatures (900–1000°C). A ceramic catalyst (based on TiO_2 and V_2O_5) reduces the temperature need to 200–300°C and enhances the efficiency of the reaction from 70–80 up to 90%. With proper design, the catalyst can also be utilized to oxidize polychlorinated dibenzo-dioxins and furans (PCDD/Fs). Sometimes activated carbon filters are employed as a final stage to adsorb organic compounds (e.g. PCDD/F), metallic mercury (Hg^o) and other trace pollutants passing the previous APC stages.

State-of-the-art combustion and APC systems destroy organic and remove inorganic pollutants with high efficiency. Various full-scale plants demonstrate the reliability of these technologies; they operate at emissions way below the stringent emission limits enacted, e.g. by the European Union (EC, 2000). Figure VI.3.6 exemplifies the development of MSW incineration emissions over the past 70 years.

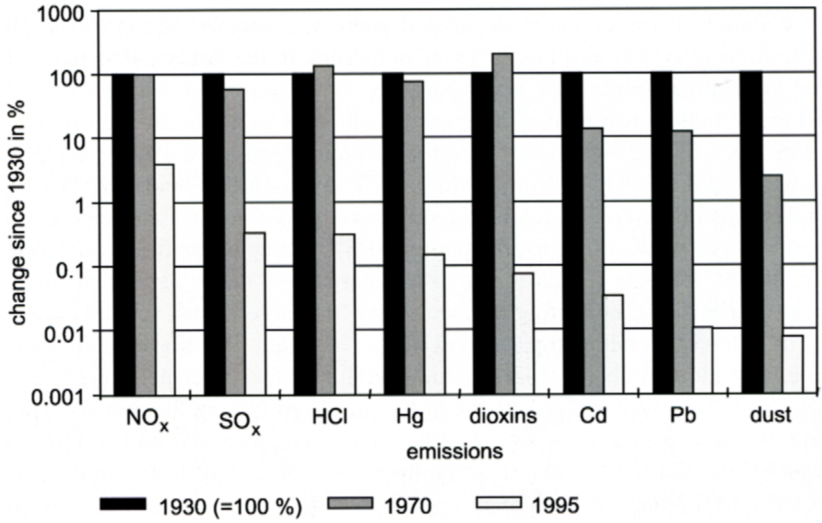

Figure VI.3.6. Reductions of MSW incineration emissions from 1930 to 1995 as a result of improved APC technology. Modern APC technology can decrease emissions to levels that are orders of magnitude lower than emission limits set by advanced environmental protection legislation. Values given are for single, state-of-the-art MSW incinerators in 1930, 1970 and 1995.

Emissions have been reduced by one (e.g. NO_x) to four (e.g. particulates, Pb) orders of magnitude. Note that particulate removal by ESP alone (standard filter technology until 1980) is not sufficient for MSW incineration. Today, state-of-the-art MSW incinerators are of no relevance anymore on a national emission inventory level. Figure VI.3.7 and Table VI.3.2 show this for SO_2 and PCDD/PCDFs for Germany and Austria. Similar results are obtained when heavy metals and other air pollutants such as NO_x and dust are discussed.

State-of-the-art APC systems of the 1990s comprised several processes such as ESP, multi-stage scrubber, $DeNO_x$ catalyst for the reduction of nitrogen oxides (Thomé-Kozmiensky, 1993). In order to reduce capital and operation costs, engineers have developed more compact APC systems with few treatment steps only. Adsorbing and absorbing substances are injected into and removed from the flue gas stream in two consecutive processes. The result of such an APC system is a mixture of fly ash, reaction and injection products. Drawbacks are higher quantities of filter residues and residues less suited for landfilling due to high fractions of mobile salts, and mixed and diluted pollutants in one stream of residues only. The latter point is in conflict with recovery goals, e.g. for metals recycling from fly ash.

Another field of research and development is how to produce: (1) bottom ash and filter residues that have improved landfill properties with regard to composition and emissions; and (2) residues that can be utilized as secondary resources. This can be achieved by either after-treatment of bottom and/or fly ashes in thermal and/or chemical processes or designing new technologies that are not necessarily based on the grate furnace technology. Bottom ashes can also be further treated by mechanical processes (sieving, screening) and magnetic separation of iron scrap. Adequate thermal after-treatment of bottom ash results in three products: (1) a silicate product that can be utilized for construction purposes; (2) a metal melt containing mainly iron, copper and other lithophilic metals (metals of low vapor pressure); and (3) a concentrate of atmophilic metals. The latter two fractions can be recycled in the metal industry. In a few European countries (Germany, Denmark,

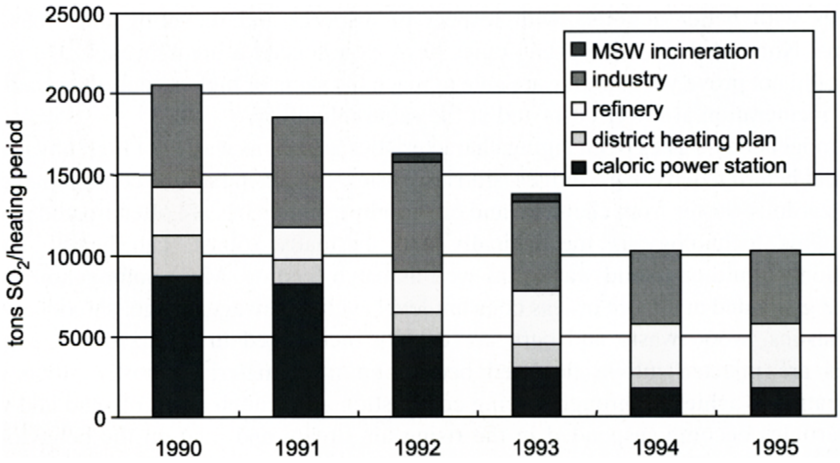

Figure VI.3.7. Contribution of MSW incineration to SO_2 emissions in Austria (König et al, 1997).

Table VI.3.2. Contribution of state-of-the-art MSW incineration to national emissions of dioxins and furans.

Country	Total emissions of PCDD/PCDF (g TEQ/a)	Contribution of MSW incineration[a] to PCDD/PCDF	
		g TEQ/a	%
Germany[b]	800–1200	5.5	0.5–0.7
Austria[c]	50–320	5.53	0.2–1.1

Modern incineration is a minor source of PCDD/F.

[a] Assuming all MSW is incinerated.

[b] Wintermeyer and Rotard (1994).

[c] Orthofer and Vesely (1990).

the Netherlands), some of the bottom ash is upgraded (crushing, sieving, curing through wet storage) and used as aggregate substitutes for road construction. However, the resource recovery effect is modest. Baccini and Bader (1996) investigated the potential of bottom ash to replace gravel in Switzerland. They found that even if 90% of MSW (360 kg/capita year) are incinerated, bottom ash could only substitute 2% of the 4.6 t of gravel utilized per capita. On the other hand, significant quantities of copper, chromium and other lithophilic metals are directed into buildings and roads by the utilization of bottom ash for construction.

Fly ash can be vitrified to produce an immobilized product for landfilling, or metals can be chemically and thermally extracted for recovery. Immobilization can also be achieved by solidification/stabilization when additives such as cement are used to physically and/or chemically immobilize hazardous substances in ashes.

Some new incineration concepts combine pyrolysis and high temperature processes with conventional APC as described above. Goals of these technologies are to produce residues with better qualities with respect to disposal and recycling than mass-burn systems. None of these new technologies have experienced a breakthrough. Up to now, they could not prove yet that they are able to reach the same or higher goals than traditional MSW incineration at lower costs and at the same reliability.

Homogeneous wastes of changing characteristics as well as wastes of high physical and chemical heterogeneity, e.g. sludges, slurries, pastes, liquids in barrels, contaminated soils and hazardous wastes from chemical and other industry branches are often treated in rotary kilns. This technology is mechanically and thermally robust, can handle gaseous (injection), liquid and solid wastes, as well as batch feeding. More homogenous wastes that are generated at a more or less constant level such as sewage sludge, shredded wastes like plastics, wood waste and bark are usually incinerated in fluidized bed furnaces. Wastes are injected into a fluidized bed of an inert material (mostly silica sand). Fluidization is achieved through forcing combustion air through a bed of sand and waste. The particles become suspended in the rising air stream and take on the behavior of a turbulent liquid. This reactor is characterized by excellent mixing conditions, which results in a fast heat exchange and mass transfer (no temperature peaks and therefore no production of thermal NO_x at operation temperatures between 800 and 900°C). The heated sand buffers variations in the calorific value, allowing the treatment of wastes with low and varying energy content. Limestone to bind SO_2 and other surface-active substances to remove pollutants can be injected into the bed or the flue gas stream. Rotary kilns as well as fluidized bed boilers can be equipped with standard APC devices.

Wastes contaminated by organic substances such as waste oil and spent solvents can be utilized as an alternative fuel in cement rotary kilns. High combustion temperatures (2000°C) guarantee destruction of organic compounds. If equipped with adequate APC, industrial boilers are in general a good option to utilize the energy content of combustible wastes and to conserve fossil fuels. On the other hand, wastes with metal contents similar to MSW such as mixed plastic fractions, combustible fractions from MSW and demolition debris, etc. require advanced APC systems, which industrial boilers often are not equipped with. Also, products (e.g. concrete, bricks, asphalt) should not be used as sink for heavy metals. If toxic metals are directed towards such products, the goals of waste management and sustainable materials management are not fulfilled. Metals are valuable resources that should be recovered rather than diluted and dissipated via products.

Today, incineration combined with advanced APC represents a reliable, robust, and compared to other available options, environmentally sound technology to dispose combustible and hazardous wastes. Further development should be focused on producing more residues that can be recovered in an environmentally sound manner, and to use thermal processes to turn waste management into an integrated part of a sustainable materials management.

VI.3.4. Goals of thermal waste treatment

The following goals for thermal waste treatment have been derived as a direct consequence of the objectives of waste management, the mass and composition of combustible wastes and the technological capability of thermal processes combined with APC. They are listed in the order of their historical importance.

VI.3.4.1. Volume reduction

Volume reduction of wastes was one of the first goals in solid waste management together with disinfection and energy recovery. Big cities experienced problems in waste disposal in their immediate surroundings because landfill space became scarce, and farmers did not accept MSW anymore as a "soil conditioner". Landfills were filled up and opening new landfills was difficult as a result of diminishing space, the NIMBY syndrome ("not in my backyard") and finding sites providing the geological and hydrological conditions for a state-of-the-art landfill. Waste combustion was, and still is, regarded as an excellent solution to this problem.

Incineration transfers 1 t of MSW into 700 kg of cleaned flue gas, 230–270 kg of bottom ash, ca. 30 kg of scrap iron (usually recovered in the steel industry), 20–30 kg of filter ash and possibly 1–2 kg of sludge from wastewater treatment depending on the APC technology (Fig. VI.3.8).

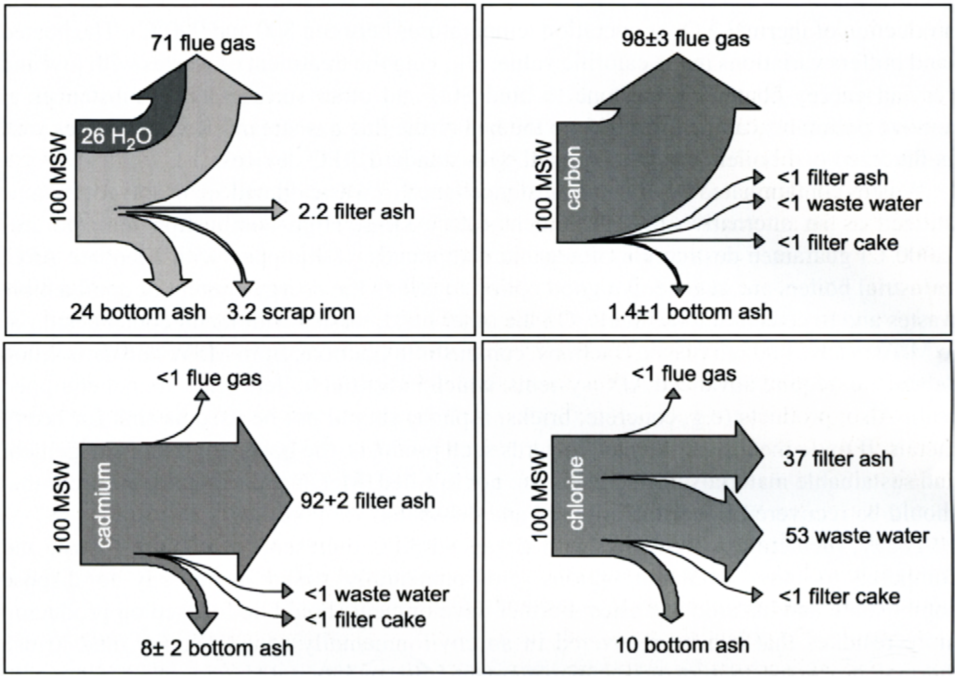

Figure VI.3.8. Mass and element partitioning by MSW incineration. The values for mass and element flows vary due to the technology applied for combustion and APC, and due to waste composition.

The specific volume of MSW in a landfill is between 1 and 2 m^3/t depending on waste compaction, composition and disposal time (Rhyner et al., 1995). Bottom and fly ash have a specific volume of ca. 0.6–0.7 m^3/t. This results in a total volume reduction of some 80–90%. Bottom ash landfills do not need a gas collection and treatment system like MSW landfills. The leachate collection system is similar to a state-of-the-art MSW landfill; since ash leachates do not contain large amounts of organic carbon and nitrogen as in the case of MSW, leachate treatment systems can be much simpler than in the case of MSW landfills. Replacement of MSW landfilling by incineration and bottom ash landfilling prolongs the lifetime of a landfill by a factor of 10. Filter residues and sludge that contain higher concentrations of heavy metals than bottom ashes have to be disposed off in safe landfills that are not in contact with the hydrosphere and that are capable of retaining hazardous substances for very long time periods. Separated and specially equipped compartments, the so-called mono-fills, or underground disposal facilities such as empty mines and salt domes serve this purpose. In principle, there are technologies available that turn bottom ashes into a substitute for gravel (see Section VI.3.2). A combination of mechanical and thermal processes can achieve this. Also, when concentrated and refined, metals in fly ash can be utilized as a resource. At the moment such technologies are not yet economic but they could contribute to a volume reduction beyond 95%, achieving maximum conservation of landfill space.

VI.3.4.2. Disinfection

Nowadays, in affluent countries, the main reason for waste management is no longer to protect human health. Due to efficient collection and sound waste treatment practice, it has become rare that diseases are spread by waste materials or by inappropriate waste management. The situation is completely different in developing countries: it has been stated that for a given amount of money, the improvement of waste management practice could save more lives and contribute more to the general health than any other single measure. One of the reasons is that waste materials can pollute surface and groundwater and thus pose a threat to the health of large populations that depend on rivers and wells for drinking water. Other reasons are infections from food grown on waste contaminated land or from food contaminated during processing and transport.

At the end of the nineteenth century, a few European cities were disposing off their municipal wastes by spreading them on agricultural fields. Due to rising hygienic problems, they started to incinerate wastes. Even simple thermal treatment resulted in a sterile waste that was hygienically safe for landfilling. Rodents and birds could not feed from ash landfills, and thus the spreading of diseases by improper waste management was brought to a close. Today's modern incinerators operate at 850–950°C and produce sterile bottom ash, filter residues, wastewater and off gas.

Recently, the potential of thermal waste treatment to destroy harmful microorganisms has been "rediscovered". Hygienic crises such as bovine spongiform encephalopathy (BSE; mad cow decease) resulted in large masses of materials that were used as a feedstock in the past and suddenly turned into waste because of new legal requirements to stop the spreading of BSE. Since these materials were infectious, they could not be landfilled, composted or recycled. The only way to dispose them was incineration. At present, MSW incinerators, hazardous waste incinerators and cement kilns are successfully treating infectious wastes. For future accidents and catastrophes, it appears essential to have thermal treatment plants that can handle large amounts of contagious wastes in a safe way.

VI.3.4.3. Energy recovery

Already at the end of the nineteenth century, energy was recovered from waste, e.g. in Oldham, England; Hamburg, Germany; and Brussels, Belgium. The motivation at this time was the production of steam in a waste heat boiler for internal power use and electricity production.

Nowadays, the motivation for energy recovery from waste is:

- conservation of non-renewable energy resources;
- reduction of greenhouse gas emissions (decrease of CO_2 emissions by burning renewable carbon in waste instead of fossil fuels);
- cost reduction of waste incineration by the production and sale of electricity and heat.

Depending on the criteria such as the energy market and the location of the waste incinerator plant (proximity of clients to buy steam/heat), incinerators are designed to produce electricity, heat (steam and/or hot water) or a combination of both. The following criteria are essential for a commercial production of steam for industrial applications and heat for district heating: (a) constant energy demand (summer and winter) and (b) short distances to the consumer(s) with an existing distribution network. The key property for energy generation is the heating value of the waste. The heating value historically has risen during the last 50 years. Nowadays, in industrialized countries, MSW has a heating value (approximately 10 MJ/kg) close to that of brown coal, thus making MSW an interesting energy source. Economic drawbacks of energy from waste are high investment costs for flue gas cleaning systems, operation costs due to auxiliary material consumption, disposal costs for residues and corrosion problems.

The overall energy recovery potential of all combustible wastes of a central European country (e.g. Switzerland, Austria or Germany) is estimated to be about 5–10% of the average national energy consumption. The potential of certain hazardous materials in the same combustible wastes is much larger (Fig. VI.3.3): about 40–50% of the total amount of cadmium and mercury used in Austria is contained in combustible wastes. Thus, the primary focus in thermal waste treatment should be on material management, and only secondly on energy recovery. Aspects of human and environmental protection are more important!

VI.3.4.4. Environmental protection

For long time periods, MSW incinerators polluted the environment severely and with long-lasting effects. The main contaminants until the 1950s were dust, heavy metals and organic products of incomplete combustion in the flue gas. Hence, the first regulation concerned dust removal. Due to the increasing content of polyvinyl chloride in MSW, off gases of MSW incinerators become increasingly acidic. Wet scrubbers were introduced to control acids. A major breakthrough in APC policy was the regulation of volatile metals in the flue gas: to reach the new emission limits of 0.1 mg Hg/N m^3, advanced APC technologies had to be developed. It became necessary to remove small particles below 1 μm, acids such as HCl, HF, SO_2 and NO_x and reduce the emissions of PCDD and PCDF by activated carbon or other means. Today's technology for APC allows meeting emission values that are one to three orders of magnitude below existing advanced emission regulation limits. Figure VI.3.6 displays the tremendous progress and reduction in emissions from MSW incineration that was achieved during the last 70 years. Table VI.3.2 and Figure VI.3.7 show that if MSW incinerators are equipped with state-of-the-art APC devices, emissions are much smaller than pollutant flows from other sources. Thus, priority of APC strategy has to be given to these other sources. Table VI.3.3 serves as an example of such sources: if MSW is combusted in a stove of a private home, the emissions are about three orders of magnitude larger than that in an MSW incinerator with appropriate APC. Since it has become popular to replace traditional oil or gas-based furnaces by wood furnaces, it is important to make sure that burning wastes in such home furnaces without APC device does not take place.

A second issue for environmental protection is climate change and greenhouse gas emissions. Hackl and Mauschitz (2000), have shown that the contribution of MSW incineration to the reduction of greenhouse gas emissions can be substantial. Schachermayer et al. (1999) have calculated that half of the reduction goal set by the Austrian Federal Government can be reached if Austria changes from present day waste management to an incineration scenario where all combustible wastes are incinerated in

Table VI.3.3. Emissions from burning waste in household furnaces and in state-of-the-art MSW incinerators.

Emissions	Dust (g/t)	HCl (g/t)	SO_2 (g/t)	NO_x (g/t)	CO (g/t)	Hg (g/t)	Dioxins (mg TEQ/t)
Household	30,000	5,300	1,000	2,000	60,000	1	3,200
MSW incineration	40	40	150	400	200	0.3	3

Even if only a small percentage of MSW is disposed off in inappropriate combustion devices, this can result in comparatively large emission flows to the environment.

MSW incinerators, cement kilns and industrial boilers, and no untreated wastes are landfilled anymore.

Residues of incineration such as bottom ash, filter ashes, scrubber water and filter cakes are a third environmental topic. They have neither the same composition as the earth's crust, which would qualify them as a building material, nor are they sufficiently highly concentrated to qualify as an ore. Hence, these materials have to be further treated (see below) and/or purified (wastewater).

VI.3.4.5. Complete mineralization

MSW contains many hazardous organic substances. Separation and input control will not be able to reduce much of these compounds. When composted or landfilled, these substances may enter the environment. The objective of incineration is to completely transform organic carbon to CO_2. Due to the physical and chemical heterogeneity of MSW and other wastes and the changing waste composition, it is in general more difficult to oxidize wastes than conventional fuels such as coal, oil or gas. Hence, the mineralization rate (defined as the percentage of carbon that is converted to CO_2) of MSW incineration is lower than that of other thermal processes.

There are two reasons why a mineralization rate of 99.9% is desirable: first, bottom ash will contain less organic carbon, hence landfilling of the ash will result in a leachate with low dissolved carbon content. Low organic carbon in the bottom ash means also not enough carbonic acid resulting from biochemical degradation of organic carbon to mobilize metals in the bottom ash. Second, a high mineralization rate means less organic compounds and products of incomplete combustion in the off gas and the fly ash particles, yielding less dioxins too. Hence, also from the points of view of air pollution and filter residue disposal, a high mineralization rate is favorable.

VI.3.4.6. Immobilization

In Section VI.3.2, it was shown that a large amount of hazardous materials and heavy metals is introduced into the anthroposphere. Waste management serves the purpose of a filter between the anthroposphere and the environment. Waste incineration may release only such substances into water, air and soil that are environmentally compatible. Since the flow of substances through the stack is very low (except for carbon, see Figure VI.3.8), most substances will remain in the solid residues. The solids may be partially recycled (see below) or have to be landfilled. In order to stay in the landfill, they must be immobilized before disposal. Bottom ash as an alkaline material that was soaked in water for some time, contains much less mobile substances than the dry filter residues that contain large amounts of readily soluble chlorides. Filter cake on the other hand is less soluble because it has been precipitated from wastewater. For any residue, pretreatment is necessary before landfilling. The goal of this treatment is the immobilization of heavy metals. It has to be taken into account that redox conditions, pH and other chemophysical parameters can change considerably in long time periods (centuries to millennia).

VI.3.4.7. Concentration

It has been described that certain elements can be significantly enriched in certain products of incineration (Brunner and Mönch, 1986). Figure VI.3.8 shows that 92% of cadmium can be concentrated in the filter ash during MSW incineration. Atmophilic metals are to a large extent transferred to the flue gas and thus collected in the filter residues such as ESP ash or filter cake. Since these residues amount to only a few percent of the total waste incinerated, atmophilic metals become highly enriched in the residues.

Chlorine is also mainly transferred to the flue gas and is washed out in the first scrubber stage. Carbon is completely transferred to the flue gas. More than 80% of the iron is found in the product of magnetic separation of the bottom ash, making scrap iron recycling a profitable business for MSW incinerators.

The concentration effect of volatile metals in the filter residues has two benefits: first, bottom ash gets comparatively "cleaner", making it a product better suited for reuse as a construction material. Second, filter ash becomes more like an ore, enabling recycling of metals. More recently, the incineration process as a whole has been investigated in view of concentrating certain elements in certain products. It is likely that the next generation of incinerators perform better in view of controlled concentrating and diluting of elements.

VI.3.4.8. Materials recycling

Figure VI.3.9 displays the total flow of cadmium through a modern economy: about 25% of the cadmium imported is eventually found in MSW. If all wastes are incinerated in state-of-the-art incinerators, more than 80% of the cadmium entering the incinerator will be concentrated in the filter ash. By a second thermal treatment, this filter ash can be further upgraded, yielding a metal concentrate well suited for recycling. Hence, 20% of the national import can be substituted by the incineration of MSW.

At present, this scheme of cadmium recycling is not economically beneficial if done in a decentralized and small-scale way. For the future, it seems feasible to collect and store filter residues for several decades and then centrally process these materials for metal recovery. Due to the better economy of scale and the high concentration, it may become more economic to produce metals by this recycling scenario than by traditional mining. Hence, in the future, thermal treatment may contribute to energy supply and materials recycling too.

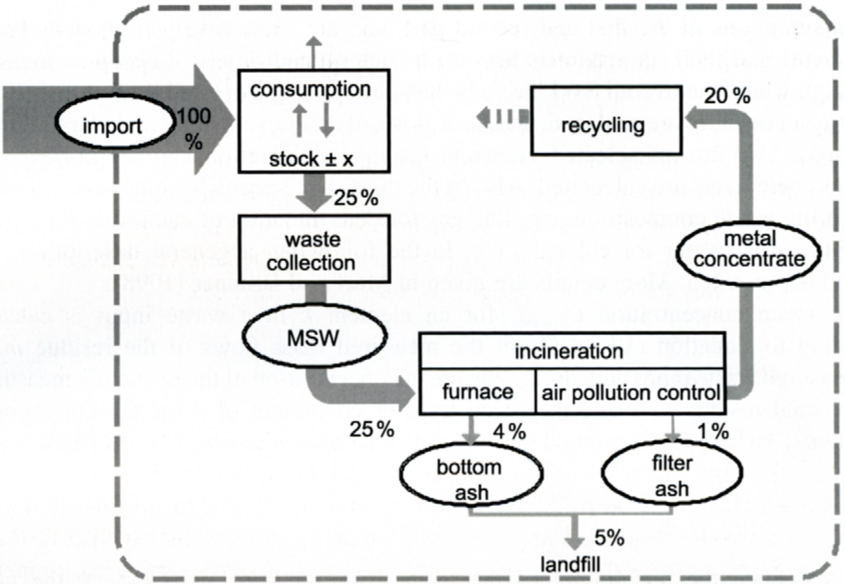

Figure VI.3.9. Materials recycling by incineration: since about 25% of the imported cadmium is finally found in combustible wastes, and by incineration more than 80% of this cadmium is transferred to filter residues, the recycling of cadmium and other atmophilic metals by thermal processes seems feasible.

VI.3.5. The municipal incinerator as a monitoring tool

Information about waste composition is crucial for planning and decision making in waste management. Efficient methods are needed to assess the effect of legislative, logistic and technical measures on the waste stream. Routine determination of waste composition and trends is essential to assess the effect of such measures. Various approaches to characterize wastes have been described previously. It has been proposed to determine elemental waste composition by investigating the material flux through an MSW incinerator plant (Brunner and Ernst, 1986). If all residues of the incineration are analyzed and the total input and output mass flows are determined over a certain period of time, the composition of the input to the plant can be calculated. This allows determining the flux of selected elements through an MSW incinerator, calculate the chemical composition of the waste input and assess the partitioning of selected elements in the SWI. The method has been successfully applied before (Agenend and Trondt, 1990; Reimann, 1989; Schachermayer et al., 1993; Vehlow, 1993; Belevi, 1995). More recently, the method was further developed to routinely monitor the waste composition by the analysis of a single incineration residue only (Morf and Brunner, 1998).

The new method consists of three parts. First, a general model is established to calculate the chemical composition of the waste input by the analysis of a single incineration residue. Second, a sampling model is developed and optimized to minimize sampling costs (samples, sample frequency and size). In the third part, parameters such as transfer coefficients (the partitioning of the elements from the waste input into the different residues) and variance of transfer coefficients are identified. They are already needed as base assumptions in the first and second part, and are successively improved. Transfer coefficients and their uncertainties have to be determined in a well-designed measuring campaign where the overall SWI has to be balanced during a defined time period. For this purpose, all residues are analyzed, and mass flows of all relevant input and output flows are measured. The flux of selected elements through incineration and the corresponding transfer coefficients are calculated. Also in the third step, specific residues are selected for monitoring waste composition, e.g. flue gas for determination of cadmium, filter ash for cadmium, wastewater for chloride, etc. In the following, a general description of the method is presented. More details are given in Morf and Brunner (1998).

The mean concentration $\bar{C}_{k,\text{waste}}$ for an element k in a waste input is calculated according to Equation (VI.3.1) from the measured mass flows of the residue $\dot{m}_p$ and the measured waste input flow $\dot{m}_{waste}$, the mean concentration of the element k measured in the selected residue $\bar{C}_{k,p}$ and the mean transfer coefficient of k for the corresponding residue $\bar{\varepsilon}_{k,p}$ (which is determined in an earlier measuring campaign; third part).

$$\bar{C}_{k,\text{waste}} = \frac{\dot{m}_p}{\dot{m}_{\text{waste}}} \frac{\bar{C}_{k,p}}{\bar{\varepsilon}_{k,p}} = P\frac{\bar{C}_{k,p}}{\bar{\varepsilon}_{k,p}} \tag{VI.3.1}$$

To calculate the uncertainty of the mean concentration, $\text{Var}(\bar{C}_{k,\text{waste}})$, the law of propagation of error is applied on Equation (VI.3.1). The result may be simplified if the covariance terms prove to be small compared to the variance terms. This has to be checked individually. If it can be assumed that the variance of routinely measured waste and residue mass flows and any covariance terms are negligible in a first order approximation, the propagation of error applied on Equation (VI.3.1) yields Equation (VI.3.2):

$$\text{Var}[\bar{C}_{k,\text{waste}}] = \left(\frac{P}{\bar{\varepsilon}_{k,p}}\right)^2 \text{Var}(\bar{C}_{k,p}) + \left(\frac{P\bar{C}_{k,p}}{\bar{\varepsilon}^2_{k,p}}\right)^2 \text{Var}(\bar{\varepsilon}_{k,p}) \tag{VI.3.2}$$

where P is the ratio of the measured residue versus the measured waste mass flow, $\text{Var}(\bar{C}_{k,p})$ the variance of the calculated mean concentration of element k in the selected residue p and $\text{Var}(\bar{\varepsilon}_{k,p})$ the variance of the mean transfer coefficient of element k from the waste into the residue p.

The approximate 95% confidence interval for the mean concentration μ in the time period considered is given by Equation (VI.3.3).

$$\left[\bar{C}_{k,\text{waste}} - 2\sqrt{\text{Var}(\bar{C}_{k,\text{waste}})} < \mu < \bar{C}_{k,\text{waste}} + 2\sqrt{\text{Var}(\bar{C}_{k,\text{waste}})}\right] \tag{VI.3.3}$$

The mean transfer coefficient for the element k into the residue p, ($\bar{\varepsilon}_{k,p}$) and the variance $\text{Var}(\bar{\varepsilon}_{k,p})$ are to be determined experimentally by an earlier substance flow analysis (third part).

The method was first applied in the MSW incinerator Spittelau, Vienna, Austria in 1999, and is routinely applied to determine waste composition since then. The capacity of the incinerator is 34 t/h of MSW. Figure VI.3.5 shows the incinerator with waste heat boiler, flue gas cleaning and wastewater treatment system as well as the measuring points for monitoring selected elements (C, Cl, Fe, Hg, Cu, Cd, Pb and Zn).

First results of MSW concentrations are shown in Figures VI.3.10 and VI.3.11: monthly mean values of Cl and Hg vary up to a factor two (Fig. VI.3.10). Daily flows of the two

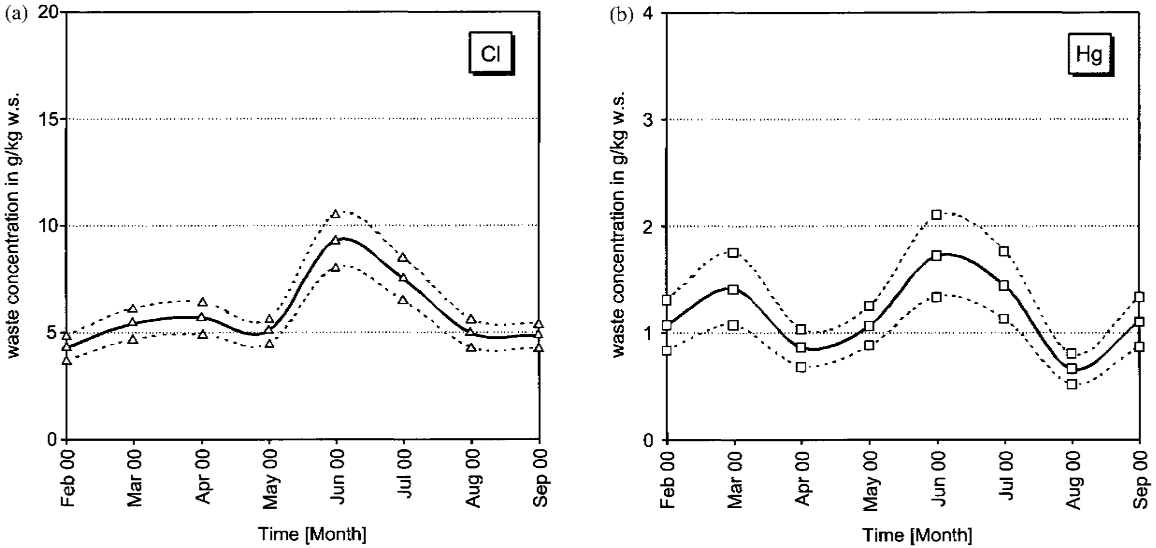

Figure VI.3.10. Time trends for monthly mean MSW concentrations of (a) chlorine and (b) mercury as determined for the Vienna MSW incinerator Spittelau, Austria between February 1 and September 30, 2000; given are means and lower and upper limits for an approximate 95% confidence interval (w.s. = wet substance) (Morf et al, 2001).

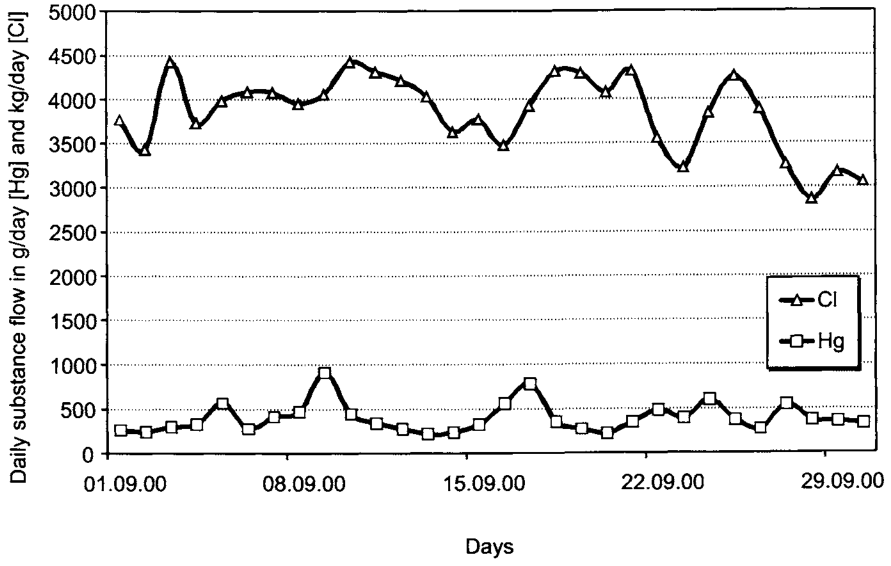

Figure VI.3.11. Time trends for daily flows of Cl [kg/day] and Hg [g/day] through the MSW incinerator Spittelau, Austria between September 1 and September 30, 2000 (Morf et al, 2001).

selected elements, Cl and Hg, vary quite substantially (up to a factor of four) within a period of a few days (Fig. VI.3.11). Both concentrations (Cl and Hg) were analyzed continuously together with the corresponding mass flows of wastewater and acid scrubber discharge, respectively. Daily substance flows in the waste input were calculated using previously measured transfer coefficients.

The proposed method to routinely monitor waste composition by analyzing single incineration residues has significant advantages regarding data quality and costs compared to the normally applied direct waste analysis. When dealing with wastes, it is of high importance to consider uncertainty and assess aspects of quality control. The use of an appropriate mathematical tool to handle substance flow analysis including error propagation is helpful.

If waste composition is measured in the same way on several MSW incinerators throughout a large region or a country, this would allow comparing the waste composition in a more cost-effective and objective way than present practice of direct waste analysis. Future MSW incinerators should be designed for and supplied with hardware and software to apply the proposed method for waste analysis. The additional costs will be small, and the return on investment large when compared to the costs and accuracy of conventional waste analysis.

VI.3.6. Conclusion

The amount of waste produced is a function of materials consumed. In the past century, material turnover in all sectors (industry, trade, agriculture, private households) has increased tremendously; there are no strong signs yet that this trend will change in the near future. Hence, the amount of wastes will further increase. Recycling can divert an important fraction of the total waste stream back to consumption. But due to energetic and economic reasons, the total recycling of wastes is not feasible. Thus, means to dispose large amounts of wastes in a safe and goal-oriented way are necessary. Goals of waste management comprise protection of man and the environment, the conservation of resources such as energy, materials and land and after-care-free landfills (precautionary principle). Since wastes are important carriers of hazardous as well as valuable materials, waste management plays a major role in environmental protection and resource conservation.

In service-oriented economies, non-hazardous wastes are larger carriers of hazardous substances than hazardous wastes. Hence, if risks from hazardous substances are to be minimized, the environmentally safe management of non-hazardous wastes, in particular MSWs, is crucial. State-of-the-art thermal treatment is a feasible way to process many hazardous and non-hazardous wastes. There are different thermal processes available to treat waste materials; each has its specific advantages and disadvantages. Investigations into mass balances of modern thermal processes show that incinerator emissions can be much smaller than the most advanced standards. If state-of-the-art APC technology is applied, flows of heavy metals and organic substances from incinerators are of no significance when compared to other emission sources. The new question is what to do with the resulting incineration and filter residues. Results from material flow analysis point to the large potential for future reuse. If long-term scenarios are investigated, it seems feasible that certain materials such as atmophilic metals can be efficiently recycled by thermal processes. It is necessary to develop new strategies in waste management such as combining energy recovery with materials recovery. If introduced on a large scale, such reuse strategies could successfully compete with present waste management trends, which are often based on dilution strategies.

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