HAZARDOUS WASTE INCINERATION

1. Introduction

The idea of a furnace operated specifically to burn waste materials originated in England more than 100 years ago. These furnaces were originally called destructors. The term incinerator was not used until the early twentieth century. Municipalities and industries are striving to reduce the generation of waste by recycling and altering their processes. Significant quantities of waste continue to be generated (see WASTES, INDUSTRIAL) and high temperature incineration is one technology for managing them. This article focuses on incinerators for the destruction of hazardous wastes. The U.S. EPA defines hazardous wastes as "by-products of society that can pose a substantial or potential hazard to human health or the environment when improperly managed". They possess at least one of four characteristics: ignitability, corrosivity, reactivity, or toxicity (1).

Properly designed and operated incinerators can safely destroy most hazardous organic liquid and solid wastes. The thermal decomposition and oxidation that occur in incinerators are usually ensured by exposing the waste to temperatures of 800°C or higher. Adequate mixing of the waste with air ensures the oxidation of organic compounds.

As shown in Table 1, the use of incineration is somewhat limited in the United States. About 15% of total U.S. wastes generated annually are classified as hazardous waste and 9% of the hazardous waste is incinerated (see WASTE TREATMENT, HAZARDOUS WASTE). About 15% of the municipal solid waste generated is disposed of in incineration systems.

High hazardous waste incineration prices, \$70–300/t for liquids and \$680–1300/t for solids (5), discourage the use of incineration. These costs for incineration generally exceed those for alternative treatment methods such as biological, \$20–760/t; landfill, \$130–210/t; or deep well injection, \$77–1400/t (6). A primary contributor to the high operating cost of incinerators is the need for auxiliary fuel, particularly for the disposal of liquid wastes having high water content or solid wastes having low heating value. In addition, air pollution control equipment (gas scrubbers) for removing acid gases, mercury, and chlorinated dioxins

Table 1. **Summary of U.S. Waste Generated and Incinerated, Millions of U.S. Tons**

Type	Generated, 10^6 t/year	Fraction incinerated, %	Number of operating incinerators
hazardous[a]	40	9	276[b]
municipal[c]	229	15	97
Medical	0.4[d]	unknown	unknown

[a] 1999 (2).
[b] Includes boilers and industrial furnaces.
[c] 2001 (3).
[d] 1990 Estimate (4).

and furans can consume large quantities of chemicals. Moreover, because incineration systems are typically complex, highly skilled operators are required to ensure efficient and reliable operation.

U.S. regulations governing the design and operation of incinerators include the Resource Conservation and Recovery Act (RCRA), the Toxic Substances Control Act (TSCA), and the Clean Air Act (CAA). Many states are authorized to regulate hazardous waste and incinerator programs, and state regulations may be more stringent than federal.

2. Overview of the Incineration Process

A general schematic of a hazardous waste incinerator and supporting equipment is shown in Figure 1. The key elements in the process include (1) preparation of the waste for feeding, (2) combustion, (3) air pollution control, and (4) disposal of liquid and solid residues. A description of these processes is given below (4). The different types of incinerators and the control of air pollutants are discussed in subsequent sections. For a general discussion of combustion and air pollution control, (see COMBUSTION SCIENCE AND TECHNOLOGY, AIR POLLUTION; AIR POLLUTION CONTROL METHODS).

Preparation of the waste before it is fed to the primary combustor may include chemical analysis, drying, sizing, sorting, crushing, blending, and shredding. Liquid wastes may need to be screened to remove particles and may be

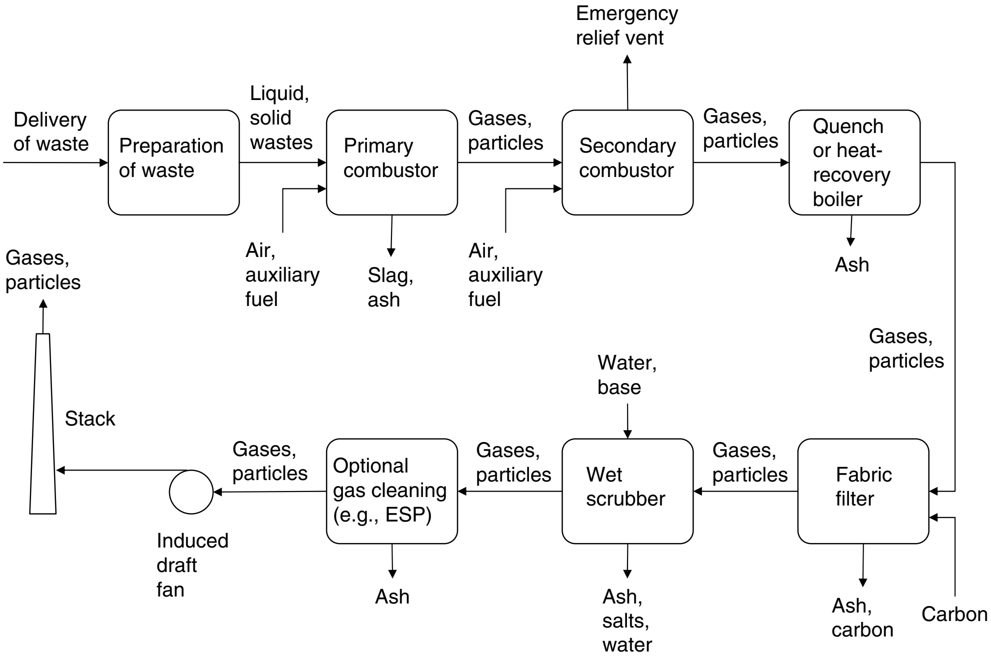

Fig. 1. Schematic of a generic hazardous waste incineration process. Not all of the elements shown here are part of every incineration process.

blended to adjust their chemical composition or increase their heating values. The blending may occur prior to feeding or in the combustor through the use of multiple injection nozzles.

The type of primary combustor selected depends on the characteristics of the waste. Common types include rotary kilns, liquid combustion chambers, fluidized beds, and various moving grate devices. Temperatures in the primary combustor may range from 700 to 1200°C and excess air may range from 50 to 250%. Average gas-phase residence times typically range from 1 to 3 s. Residence times for solids may range from seconds (for entrained solids) to 1 or more hours. Cement kilns, lightweight agregate kilns, and halogen acid production furnaces are also commonly used for incineration.

The combustion of liquids in the primary combustor occurs in steps: (1) heating of the waste to its boiling point, (2) vaporization of the waste droplets, (3) heating of any waste residue to combustion temperature, and (4) destruction by combustion reaction. Destruction of waste species volatilized during the first three steps can begin the moment a species becomes gaseous, because sensible heating of volatilized components can be rapid, and need not be considered as a separate step. The factors that govern the efficiency of liquid waste destruction include atomization (mean drop size and size distribution), temperature, residence time, O_2 concentration; and mixing.

The combustion of solids in the primary combustor involves heating, drying, pyrolysis, char gasification, char oxidation, and combustion of gas-phase species. The factors that govern the efficiency of solid waste destruction include particle size, temperature, residence time, O_2 concentration; and mixing in the solid and gas phases.

The secondary combustor is designed to provide additional time for mixing and reaction. Unburned vapors and particles leaving the primary combustor are given a second chance to be destroyed. Secondary chambers are usually supplied with fuel and air. The fuel may consist of liquid waste or auxilliary fuels like natural gas. Temperatures and excess air are similar to those in the primary combustor. Average gas-phase residence times typically range from 0.5 to 3 s.

The secondary combustor, or the duct leading from the secondary combustor to the gas cleaning equipment, may be equipped with an emergency relief vent. The vent is designed to prevent overpresurization of the downstream gas cleaning equipment during upset conditions. Upset conditions might result from overcharging the primary combustor, feeding of explosives, or steam explosions. These conditions are undersirable because they have the potential to injure workers, damage equipment, release uncombusted vapors and particles to the surroundings, and particularly concern downwind residents.

3. Types and Operation of Hazardous Waste Incinerators

The quantity (millions of U.S. tons) of hazardous waste treated by various types of facilities (2) is summarized in Table 2. Note that on-site or captive incinerators do not accept waste from outside the corporations that operates them. Table 3 (8) gives another view of the prevalence of different types of hazardous waste incinerators. The numbers in Table 3 are from the database developed by

Table 2. **Summary of Quantity of U.S. Hazardous Waste Treated by Various Facilities, Millions of U.S. Tons**[a]

Facility type	Quantity treated, 10^6 t/year	Fraction of total, %
on−site incinerators (captive)	1.01	28
cement kilns	1.03	29
commercial incinerators	0.452	13
solid-fuel boilers	0.207	6
halogen acid furnaces	0.069	2
lightweight aggregate kilns	0.064	2
liquid-fuel boilers	0.725	20

[a] Ref. 2.

EPA in order to revise air emission standards for hazardous waste combustors. Note that these numbers do not represent the totals for commercial and on-site incinerators because not all incinerators are included in this database. Table 3 does show, however, that most solid-waste incinerators are rotary kilns, and that liquid-waste incinerators are commonly used in on-site facilities. The discussion below focuses on incinerators for the destruction of solid and liquid wastes.

3.1. Rotary Kiln Incinerators. Table 3 shows the predominance of rotary kiln incinerators for government, commercial, and on-site destruction of solid wastes. The rotary kiln is versatile because it can accept a wide variety of liquid and solid hazardous wastes. Any liquid capable of being atomized by steam or air can be incinerated, as well as heavy tars, sludge, pallets, drums, and filter cakes. This ability to accept diverse feeds is the outstanding feature of the rotary kiln. Figure 2 shows a cross-section of a commercial, slagging, rotary kiln with a secondary combustion chamber (SCC) (9,10). Fluxing agents, such as waste glass, are added to the feed of a slagging kiln to help reduce the melting point of the ash.

The major components in Figure 2 include the rotary kiln, secondary combustor, kiln burner, fuel and liquid waste injection lances, solids feed chute, wet deslagger, and secondary combustor burners. For this particular facility, the

Table 3. **Summary of the Prevalence of Different Types of Hazardous Waste Incinerators**[a]

Type	Government	Commercial	On-site
solid waste incinerators			
rotary kiln	7	16	17
fixed hearth	1	2	3
moving hearth	1		
roller hearth	1		
rotary hearth	1	2	1
fluidized bed		1	4
controlled air		1	1
liquid waste incinerators	3		41

[a] Ref. 2.

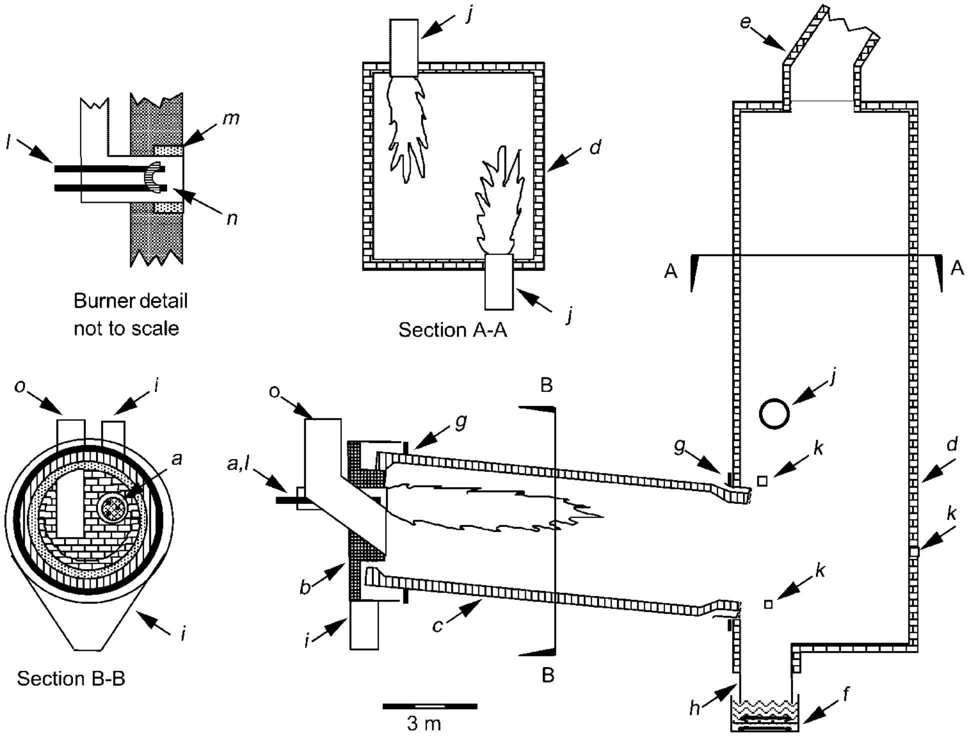

Fig. 2. Cross-section of a slagging rotary kiln with afterburner (10): (**a**), front wall multi-fuel burner; (**b**), stationary front wall; (**c**), refractory lined rotary kiln; (**d**), SCC refractory wall; (**e**), hot duct to gas cleaning; (**f**), wet deslagger; (**g**), kiln end seal; (**h**), sump wall, metal shirt; (**i**), air inlet ducts; (**j**), SCC burners; (**k**), view port and test access; (**l**), air-atomized fuel and liquid waste spray lances; (**m**), burner tile; (**n**), bluff body flame holder; and (**o**), solid feed chute.

4.4-m-diameter kiln shell is 12 m long and is lined with refractory brick. The rectangular secondary combustion chamber is 5.3 m across and 17.4 m high. The thermal rating of the plant is 35 MW. The SCC is designed to give a gas residence time of 3 s at a minimum temperature of 1370 K. Typical gas temperatures at points *k* in Figure 2 are 1400 K. Detailed temperature measurements for the wall and slag of the kiln pictured in Figure 2 are available in (9,10). The oxygen concentration at the exit of the secondary chamber typically ranges from 4 to 15% (wet). The minimum allowed value is 3%.

3.2. Fluidized-Bed Incinerator. Fluidized-bed incinerators are employed in the paper and petroleum industries, in the processing of nuclear wastes, and in the disposal of sewage sludge. These units are versatile and can be used for disposal of shredded solids, liquids, and gaseous combustible wastes.

The basic fluid-bed unit consists of a refractory-lined vessel, a perforated plate that supports a bed of granular material and distributes air, a section above the fluid bed referred to as freeboard, an air blower to move air through the unit, a cyclone to remove all but the smallest particulates and return them to the fluid bed, an air preheater for thermal economy, an auxiliary heater for start-up, and a system to move and distribute the feed in the bed. Auxiliary fuel may be added to the bed. Over a proper range of airflow velocities, usually 0.8–3.0 m/s, the solids become suspended in the air and move freely through the bed.

The fluidized bed has many desirable characteristics. Because of the movement of the particles, the bed operates isothermally and minimizes hot or cold regions. Large fluctuations in fuel quality are damped out because of the high thermal capacity of the bed. Solid particles are reduced in size in the bed until they become small and light enough to be carried out of the bed. Bed diameter is limited to ∼15 m, and the depth ranges from 0.5 to 3 m. A bed material such as limestone may be chosen to react with acidic gases, such as SO_2, to remove them from the combustion gases. Because of the excellent air-to-solid contact, the fluid bed may be operated at low excess air rates. High heat-transfer rates allow large quantities of heat to be removed by a small heat-transfer area in the bed. Fluid beds are not effective in handling materials that contain components with a low ash-melting or softening temperature.

3.3. Fixed Hearth Incinerator.

Fixed hearth incinerators are also known as controlled air or starved air incinerators. They employ two combustion chambers like the rotary kiln in Figure 2. Auxilliary fuel and liquid wastes may be fed to both chambers. Waste is pumped or ram fed into the primary chamber and partially burned with 50–80% of the air required for complete combustion (7). Air is supplied at low velocities to the primary chamber through the grate on which the waste rests. Velocities and burning rates are keep low to prevent the entrainment of particles. The resulting vapors and gases; tars, carbon monoxide, and lighter hydrocarbons; are burned with added air in the secondary chamber. The air added to the secondary chamber is 100–200% of that required for complete combustion and additional fuel or liquid waste may be added to complete the destruction process.

Fixed hearth units are generally lower in capacity and cost than rotary kilns. The ram feeding of the waste limits their capacity. Their small size and relatively low particulate control requirements make them attractive for smaller, on-site operations (7).

3.4. Moving-Hearth Incinerators.

In this type of incinerator, sometimes called a stoker, the waste moves through the furnace on a moving grate. The grate provides support for the waste, admits the under-fire air through openings, transports the waste from the feed chute to the ash quench, and agitates the bed to bring fresh charge to the surface and expose waste to oxygen and flame. In roller hearths, the waste moves through the furnace in containers on rollers. Auxilliary fuel and liquid wastes may be fed above the grate.

As the waste enters the furnace, radiation from the hot combustion gases and the refractory furnace lining heats and dries it. As it is heated further, it pyrolyzes and ignites. Combustion takes place both in the solid, to burn out the residue, and in the gas space to burn out the pyrolysis products. Overfire air jets greatly assist mixing and combustion in the overfire air space.

3.5. Rotary Hearth Furnace.

Rotary hearth furnaces are most often used for incineration of municipal and industrial sludge. The main components of the rotary hearth are a refractory-lined shell, a central rotating shaft, a series of solid flat hearths, a series of rabble arms having teeth for each hearth, an afterburner (possibly above the top hearth), an exhaust blower, fuel burners, an ash removal system, and a feed system.

The feed is normally introduced to the top hearth where the rabble arms and teeth attached to the central shaft rotate and spiral solids across the hearth to the center, where an opening is provided and the solids drop to the next hearth. The teeth of the rabble arms on that hearth spiral the solids toward the outside to ports that let the solids drop down to the next hearth. Solids continue downward, traversing each hearth until they reach the bottom and the ash is discharged. The primary advantage of this system is the long residence time in the furnace controlled by the speed of the central shaft and pitch of the teeth.

Burners and combustion air ports are located in the walls of the furnace to introduce either heat or air where needed. The air path is countercurrent to the solids, flowing up from the bottom and across each hearth. The top hearth operates at 300–550°C and dries the feed material. The vapors leaving the top hearth may contain high levels of contaminants and require treatment in a secondary combustion chamber. The middle hearths, at 750–1000°C, provide the combustion of the waste, whereas the bottom hearth cools the ash and preheats the air.

3.6. Liquid Incinerators. Liquid incinerators typically provide 0.3–2 seconds gas-phase residence time at 800–1200°C and 25–250% excess air (7). The furnace may be vertical or horizontal. Vertical furnaces are normally used for wastes that are high in salts. Nonaqueous wastes are fed through the burner, atomized, and burned in suspension. Aqueous wastes are also atomized and injected near the burner. The factors that govern the efficiency of waste destruction include atomization, (mean drop size and size distribution), temperature; residence time, O_2 concentration; and mixing.

3.7. Cement Kilns. As noted in Table 2, cement kilns are used to destroy 29% of the hazardous waste treated in the United States Because many chemical wastes have a high heating value, they can be used to supplement traditional fuels (coal, natural gas, and oil) in the cement manufacturing process. The manufacturing process is complex (see CEMENT) and there are two basic processes in use: wet and preheater-precalciner. In the wet process, the raw materials are feed to the kiln as a wet slurry. The slurry is dried, calcined, and heated to ~1500°C in kilns that are typically 150 m long. The residence time of the solids is 2–3 h. The preheater-precalciner process is more efficient than the wet process and newer kilns are of this type. In a preheater-precalciner, the slurry is preheated and calcined in a series of cyclones before it enters the kiln and consequently the kiln is relatively short.

The method of feeding hazardous waste (11) depends on the temperature and residence time required for destruction, and on the physical form of the waste. Liquids can be injected at the kiln burner by either blending with a conventional liquid fuel or by injection through a separate lance. In wet process kilns, solid wastes may be fed in the middle of the kiln through a hatch in the rotating kiln wall. In preheater-precalciner kilns, solid wastes are typically dropped in the feed end (cold end) of the kiln. Solids may also be propelled into the hot end of wet and preheater-precalciner kilns.

3.8. Lightweight Aggregate Kilns. Lightweight aggregate is a course aggregate used in the manufacture of lightweight concrete materials like concrete block, structural concrete, and pavement. The lightweight aggregate is made from crushed clays and shales which are heated in a rotary kiln to $\sim$1200°C. The gas-phase residence time is $\sim$4 s. The kilns are fired with coal, coke, natural gas, fuel oil or liquid hazardous waste. Kilns that burn liquid waste are typcially fired without auxilliary fuels (11).

3.9. Halogen Acid Furnace. A halogen acid furnace is an industrial furnace designed to producd halogen acids (primarily HCl, but also HBr and HF) from halogenated organic wastes. The wastes are burned to convert the chlorine that they contain to hydrogen chloride. The HCl is absorbed in water and recovered for reuse or neutralization.

4. Air Pollution Control and Emissions

Figure 1 shown the key air pollution control devices that are downstream of the primary and secondary combustors. The items shown and their order may vary from one plant to another. In all cases, however, the first piece of equipment is a quenching operation or heat recovery boiler that lowers the temperature of the combustion products so that they can enter the particulate control device. A general overview of air pollution control engineering and equipment is given by (12).

4.1. Baghouse or Fabric Filter. Figure 1 shows a baghouse or fabric filter after the boiler. Baghouses include a series of bags suspended in a vertical orientation through which particulate-laden gases pass. Particulates are filtered out at the bag surface. The bags are periodically shaken or rapped to allow the dust collected to fall into a hopper below. Fabrics are available that are acid resistant and withstand temperatures up to 260°C. Particulate removal efficiencies are in the 95–99% range. Figure 1 shows pulverized carbon being added upstream of the fabric fiter to control emissions of mercury and polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzo-furans (PCDF). Carbon beds may be used instead and can be located at the end of the chain of gas cleaning equipment.

4.2. Wet Scrubbers. A wet scrubber follows the fabric filter in Figure 1. There are hundreds of different types of scrubbers and they can serve two purposes: to remove particles and to remove acid gases like HCl and SO_2. If the primary purpose of the wet scrubber is to control gaseous pollutants, then a packed or plate column will serve.

HCl can be absorbed into water to make a concentrated (usually 20 wt%) HCl solution, whereas SO_2 and Cl_2 must be scrubbed using a basic reagent (usually caustic or lime) to be effectively removed. The scrub liquor pH must be controlled to avoid heavy reagent consumption caused by the removal of CO_2. Even if only HCl is present, it is usually a good idea to follow the HCl absorber with a basic scrubber in order to ensure complete elimination of acids from the exhaust gas. When absorbing chlorine into alkaline solutions, the products are both chloride and hypochlorite. It is necessary to keep the pH above nine in order to stabilize the hypochlorite and avoid regeneration of chlorine. The blowdown can be treated in one of several ways. Hypochlorite can be decomposed to chloride and oxygen using homogeneous transition-metal catalysts (13), reduced to chloride and sulfate with sulfite, or reacted with hydrogen peroxide to form chloride, water, and oxygen.

Oxides of nitrogen, NO_x, can also form during the combustion process. These are generally at low levels and at too low an oxidation state to consider water scrubbing. A basic reagent picks up the NO_2, but not the lower oxidation states; the principal oxide is NO, not NO_2. Control of NO_x is achieved by avoidance of high temperatures with high oxygen concentrations in the combustion process. If additional abatement is required, selective catalytic reduction, (SCR) is commonly used (12,14). SCR involves NH_3 injection over a bed of catalyst in the presence of oxygen.

Venturi scrubbers consist of a convergent section, a throat, and a divergent section. Particulate laden gases enter the convergent section, accelerate to approximately 130 m/s (425 ft/s), and are mixed with water via a spray system at the throat. Smaller (<0.1 μm in dia) particles are removed by diffusion; larger particles agglomerate in the water mist. Gases flow to the divergent section where velocities decrease allowing agglomerated particulates to drop out. Approximately 50–70% of particulate matter leaving liquid waste incinerator furnaces is <1 μ in diameter, making removal difficult. To effect higher removal efficiencies, pressure drop between the Venturi inlet and throat is increased to promote greater turbulence and agglomeration. Typical pressure drops range from 2.5 kPa to >25 kPa (10–100 in. water). Removal efficiencies are in the 50–99% range depending on particulate size distribution and throat pressure drop.

4.3. Electrostatic Precipitators. Both wet and dry electrostatic precipitators are generally used for polishing or small particulate removal. In dry electrostatic precipitators, a positive electrical charge is given to particles in the flowing combustion gases. The charged particles are then collected on oppositely charged plates. Collection efficiencies are a function of particle size, gas velocity, the uniformity of gas flows, both with time and across the field, the electrostatic field strength, and particulate matter electrical resistivity. Wet precipitators work on the same principles but the collection plates are wet.

4.4. Emissions of Heavy Metals. Metals entering an incinerator can leave the system with the bottom ash, the captured fly ash, or the exhaust gases. The fly ash is typically enriched with heavy metals relative to the entering solid waste. The fraction leaving with the exhaust gases can include metal vapors such as mercury and submicron particles that escape capture in the air pollution control devices. Metals entering the incinerator as liquid streams usually leave the furnace in the fly ash.

The level of enrichment of metals in the flyash increases with increasing incinerator temperature and increasing metal volatility. Pilot-scale rotary kiln data showing both effects are given in Figure 3 (15). The enrichment on small particles results from the condensation of vaporized metals. Metal concentrations on particles also typically increase with decreasing particle diameter. The vast literature on the behavior of metals in coal combustion is useful for understanding these phenomena (16). A comprehensive review on metal emissions from incinerators is available (17).

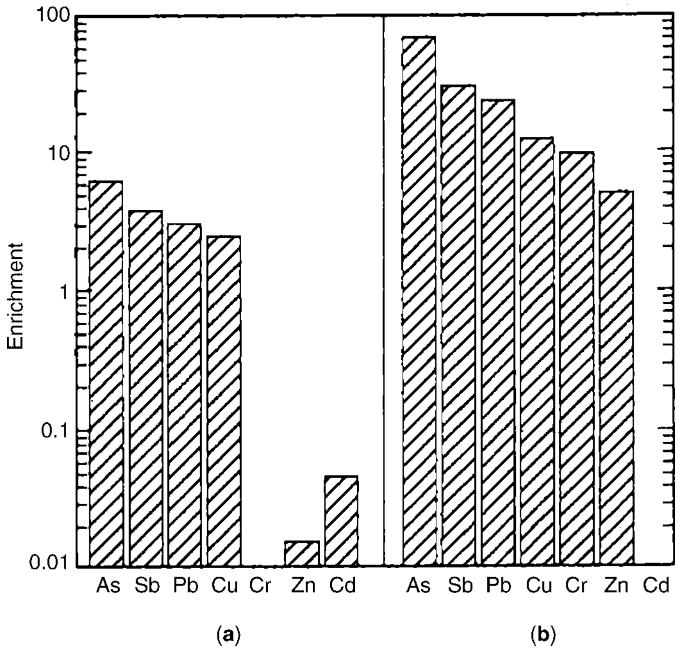

Fig. 3. The enrichment of metals in the fly ash of a pilot-scale rotary kiln as a function of temperature (**a**) at 540°C and (**b**) at 980°C (15).

The critical factor affecting the emision of mercury is its oxidation state. The chemistry of oxidized mercury in combustion gases is different from that of elemental mercury. Oxidized mercury, primarily $HgCl_2$ in flue gases from chlorine-containing wastes, is efficiently absorbed in wet scrubbers while elemental mercury is not. Oxidized mercury is also more readily adsorbed on sorbents (such as the injected carbon shown in Fig. 1) and unburned carbon. The oxidation of elemental mercury can occur in homogeneously, in the gas phase, and heterogeneously, on particles (18).

4.5. Dioxin and Furan Emissions. The emissions of polychlorinated dibenzo-*p*-dioxins (PCDD) and PCDF from incinerators (4) are of interest to the public, scientists, and engineers. The most toxic congener is 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) (7). The proposed mechanism by which chlorinated dioxins and furans form has shifted from one of incomplete destruction of the waste to one of low temperature, downstream, catalytic formation on fly ash particles (19). The optimum conditions for formation of PCDD and PCDF include (1) high particle loadings, (2) particles that are rich in Cu, (3) a signifcant gas phase residence time in the 250–350°C temperature window, (4) a poorly mixed gas phase, (5) low combustion temperatures, and (6) fuel-rich conditions (20). Extensive measurements in municipal solid-waste combustors have shown little effect of the chlorine content of the waste on the formation of PCDD and PCDF (21). It is essential that the particulate control equipment be operated at conditions that avoid the 250–350°C temperature window.

5. Challenges in Operation and Monitoring

This section briefly discusses several challenges that may be encountered in operating a hazardous waste incinerator. The challenges include "puffing" associated with the batch feeding of highly volatile, high heating value waste, loss of flame, particle entrainment, encapsulation of unburned solid waste (the burnt cabbage problem), steam explosions, slag buildup, brick and refractory failures, temperature measurement, stack sampling for mercury and other trace species, nonhomogeneous waste, and poor carbon burnout. The first three challenges are discussed below.

5.1. Puffing and Loss of Flame. The batch feeding of highly volatile, high heating value waste to rotary kilns or hearth systems can result in the rapid heating and vaporization of the waste, positive pressures in the furnace, and the potential release of unburned vapors (puffing) (22,23). The sudden vaporization of organic compounds can cause fuel-rich conditions that extinguish the flame in the primary or secondary chamber. The loss of the flame, from whatever cause, without a shutdown of the combustion air, may allow cold combustion air to pass unheated through the system, sweeping unburned vapors with it. This will occur even though the walls of the furnaces may be at combustion temperatures. The rate of convective heat transfer between the cold air and the walls is too low to permit effective heating. These circumstances also lead to the possibility of an explosion if organic vapors mix with adequate air and encounter an ignition source.

5.2. Entrainment of Particles. The gases in rotary kilns are frequently thermally stratefied (24) and the bed of solids is commonly blanketed with relatively cool air. Because kilns operate under negative pressure, the cold air is drawn in through the end seals and solids feed chute shown in Figure 2. Small particles (roughly 50 μm or less) that are entrained in this cool air, adopt its temperature and are largely unaffected by radiation heat transfer. For example, a 50-μm particle in 500 K air with surrounding surfaces at 1400 K will have a steady state-temperature of ∼600 K. The same effect will keep organic vapors that are entrained from the bed cool. The cool temperatures prevent destruction of the organic materials and contaminated particles may deposit in the ash collection system.

6. U.S. Regulations Affecting Design and Operation of Incinerators

U.S. Regulations governing the design and operation of incinerators include the Resource Conservation and Recovery Act (RCRA), the Toxic Substances Control Act (TSCA), and the Clean Air Act (CAA). Many states are authorized to regulate hazardous waste and incinerator programs, and state regulations may be more stringent than federal.

6.1. Clean Air Act. With the promulgation of the hazardous waste combustors (HWC) MACT (Maximum Achievable Control Technology) rule on September 30, 1999, the primary regulation governing air emissions from HWCs switched from RCRA to the Clean Air Act. RCRA regulations still govern how facilities handle waste, set up financial assurance and other constraints.

Previously, RCRA regulations set the limits for destruction and removal efficiency (DRE), particulate matter emissions, and chlorine/HCl emissions.

Soon after the 1999 rule was promulgated, both industry and the Sierra Club sued EPA, claiming that EPA did not follow the MACT process in setting the rules. The courts sided with the Sierra Club and vacated the rules. However, they left an opening for the interested parties to negotiate interim standards while EPA redeveloped the MACT standards for this category using revised techniques. The interim standards were negotiated and finalized on February 13, 2002. As a part of the negotiations, EPA agreed to develop permanent replacement standards by June 2005. The interim standards for new and existing incinerators are as follows.

Particulate Emission Limits. Particulate emissions, including condensables, must be demonstrated during a comprehensive performance test (similar to a RCRA trial burn) to be <34 mg/dry standard cubic meter (dscm) (0.015 grain/dry standard cubic foot (gr/dscf)) at the incinerator's stack, or lower, depending on state regulations for both new and existing incinerators. Note that in the United States, dry standard cubic meter means at 25°C, 1 atm, and 7% oxygen.

Products of Incomplete Combustion Emission Limits. Products of incomplete combustion typically are not directly measured during the comprehensive performance test. Instead, levels of carbon monoxide or total hydrocarbons (as propane) emissions are used as an indication of combustion efficiency. High combustion efficiencies are assumed to result in acceptable levels of products of incomplete combustion. If carbon monoxide emissions are measured at <100 ppmv dry basis or if the total hydrocarbons emissions are <10 ppmv dry basis for new and existing sources, the standard is met. However, during the DRE test, both the carbon monoxide and total hydrocarbon emission limits must be met.

Dioxin and Furan Emission Limits. In addition to controlling carbon monoxide or total hydrocarbons, the HWC MACT rules restrict the emissions of dioxins and furans to 0.20 ng (toxic equivalents) per dry standard cubic meter for existing sources. However, if the incinerator is equipped with a rapid quench system that lowers the temperature of the air to <205°C prior to entering the rest of the air pollution control system, the limit is modified to 0.40 ng (TEQ)/dscm. The dioxin and furan emissions standard for new sources is 0.20 ng (toxic equivalents) per dry standard cubic meter.

Metal Emission Limits. Limits for metals, both carcinogenic and noncarcinogenic, are grouped into three volatility categories and limits are set for each category. Mercury is the only high volatile metal. The emission limits for mercury are 45 ug/dscm for new sources and 130 ug/dscm for existing sources. The emission limits for semi-volatile metals (lead and cadmium) are 120 ug/dscm for new sources and 240 ug/dscm for existing sources. The emission limits for low volatile metals (arsenic, beryllium, and chromium) are 97 ug/dscm for both new and existing sources. Additional limits may be set on these or other metals under RCRA omnibus authority (see the RCRA section below).

HCl and Cl Emission Limits. Hydrochloric acid and chlorine emission limits are 21 ppmv (parts per million by volume) for new sources and 77 ppmv for existing sources.

Destruction and Removal Efficiency. In preparation for a trial burn or the comprehensive performance test, the owner or operators prepares an analysis of the waste feed stream. Roughly 400 principal organic hazardous constituents (POHCs) are listed in the *Code of Federal Regulations* (25,26), and if the waste analysis includes POHCs, these are listed along with their concentrations in the incinerator permit application. A permit writer from a government agency, eg, the U.S. EPA, selects one or more POHC to be used during the trial burn to demonstrate the incinerator's DRE. The writer bases the selection on difficulty of incineration, ie, low heating value or high thermal stability, and concentration. Constituents having concentrations less than ~100 ppm are likely not to be selected because of difficulty in analytical detection of such small quantities at 99.99% or greater DRE. During the trial burn, for each POHC selected, the incinerator must demonstrate a DRE of 99.99% or greater for RCRA wastes, and 99.9999% for polychlorinated biphenyl (PCB) or dioxin wastes (under TSCA).

The DRE is defined by

$$\mathrm{DRE} = \frac{W_{\mathrm{in}} - W_{\mathrm{out}}}{W_{\mathrm{out}}} \times 100 \tag{1}$$

where W_{in} is the mass feed rate of a contaminant and W_{out} is the mass emission rate of the same contaminant at the stack to the atmosphere. Metals limits were promulgated for boilers and industrial furnaces that burned hazardous waste but were never promulgated for incinerators. However, limits from these rules were often included in hazardous waste incinerators using RCRA's omnibus provisions.

6.2. Resource Conservation and Recovery Act. The RCRA, Subtitle C, regulates hazardous waste disposal. It identifies wastes as being hazardous if falling into one or more of the following categories: ignitable, eg, having a flash point <60°C; corrosive, eg, having a pH <2 or >12.5; reactive, eg, reacting violently when mixed with water; toxic, as determined by the toxicity characteristic leaching procedure (26) (see TOXICOLOGY), or listed in Subtitle C as a hazardous waste from nonspecific sources, industry-specific sources, or as an acute hazardous or toxic waste.

As stated above, the RCRA administrative standards remain in effect even though the air emission standards are now included in the clean air act regulations. Administrative standards include procedures for waste analysis, inspection of equipment, monitoring, and facility security. Steps needed to meet administrative standards are outlined in the permit. Operating conditions are included in either the Title V permit or the RCRA permit to assure ongoing compliance with the performance standards.

Under the mixture and derived from rule, ash from a hazardous waste incinerator must be treated as a hazardous waste under RCRA, Subtitle C regulations, unless it has specifically been shown to be non-hazardous. Potential ash and liquid waste streams are shown in Figure 1.

RCRA Omnibus Authority. Because the Clean Air Act does not have comparable provisions, the EPA retained their omnibus authority under RCRA to impose additional permit condition if it is determined that the interim MACT standards are not sufficient to protect human health and the environment. Most of the time, this means that either the facility or the permitting authority will conduct a site-specific risk assessment using multi-pathway protocols. Draft protocols are found on EPA's hazardous waste combustion web site (27).

6.3. Other Federal Regulations. The TSCA regulates the operation of incinerators disposing of waste containing >50 ppm PCBs. Such units must demonstrate a DRE of 99.9999% during a trial burn prior to obtaining an operating permit. In addition, certain facilities may have restrictions on emissions of ozone, sulfur dioxide, and nitrogen oxides. The Clean Air Act intends to maintain National Ambient Air Quality Standards (NAAQS) for each of these pollutants in attainment areas, and to improve the quality of air in nonattainment areas. This regulation may be more restrictive than RCRA because it specifies the type of emission control technology to be used when the potential to emit exceeds specified levels (see AIR POLLUTION; AIR POLLUTION CONTROL METHODS).

BIBLIOGRAPHY

"Incinerators" in *ECT* 3rd ed., Vol. 13, pp. 182–206, by B. B. Crocker, Monsanto Co., and R. C. Bailie, West Virginia University; in *ECT* 4th ed., Vol. 14, pp. 86–122, by R. Bertrum Diemer, Jr., and Thomas D. Ellis, E. I. du Pont de Nemours & Co.; Inc. and Geoffrey D. Silcox, JoAnn S. Lighty, and David W. Pershing, University of Utah; "Incinerators" in *ECT* (online), posting date: December 4, 2000 by R. Bertrum Diemer, Jr., and Thomas D. Ellis, E. I. Du Pont de Nemours & Co., Inc. and Geoffrey D. Silcox, JoAnn S. Lighty, and David W. Preshing, University of Utah.

CITED PUBLICATIONS

1. U.S. Environmental Protection Agency, *Terms of the Environment*, http://www.epa.gov/OCEPAterms/hterms.html, last accessed May 2004.
2. U.S. Environmental Protection Agency, *The National Biennial RCRA Hazardous Waste Report (Based on 1999 Data)*, EPA530–S–01–001, Washington, D.C., June 2001. http://www.epa.gov/epaoswer/hazwaste/data/brs99/, last accessed January 2004.
3. U.S. Environmental Protection Agency, *Basic Facts: Municiple Solid Waste*, 2001, http://www.epa.gov/msw/facts.htm, last accessed January 2004.
4. C. C., Lee, Medical Waste Incineration Handbook, Government Institutes, Inc., Nov. 1990, pp. 2–10.
5. Office of Solid Waste, U.S. Environmental Protection Agency, *Assessment of the Potential Costs, Benefits, & Other Impacts of the Hazardous Waste Combustion MACT Standards: Final Rule*, Washington, D.C., July 1999, Exihibit 3–1, pp. 3–4.
6. U.S. Environmental Protection Agency, *Estimating Costs for the Economic Benefits of RCRA Noncompliance*, Washington, D.C., December 1997, Table 5–3, pp 5–10.
7. C. R. Dempsey and E. T. Oppelt, *J. Air Waste Manage. Assoc.* **43**, 25–78, (1993).
8. U.S. Environmental Protection Agency, NESHAP, *Standards for Hazardous Air Pollutants for Hazardous Waste Combustors (Final Replacement Standards and Phase II) – Notice of Data Availabilty, Federal Register*, Vol. 67, No. 127, July 2, 2002.

9. J. M. Veranth, D. Gao, and G. D. Silcox. *Environ. Sci. Technol.* **30**, 3053, (1996).
10. J. M. Veranth G. D. Silcox and D. W.. Pershing, *Environ. Sci. Technol.* **31**, 2534, 1997.
11. J. J. Santoleri, in J. J. Reynolds, and L. Theodore, Introduction to Hazardous Waste Incineration, 2nd ed., Wiley-Interscience, New York, 2002.
12. W. T. Davis, ed., Air Pollution Engineering Manual, 2nd ed., John Wiley & Sons, Inc., New York, 2000.
13. M. W. Lister, *Can. J. Chem.* **34**, 479 (1956).
14. C. N. Satterfield, Heterogeneous Catalysis in Practice, McGraw–Hill Book Co., New York, 1980, pp. 229–231.
15. D. A. Tillman, W. R. Seeker, D. W. Pershing, and, K. DiAntonio, *Remediation, 251 (summer 1991).*
16. R. C. Flagen and J. H. Seinfeld, Fundamentals of Air Pollution Engineering, Prentice Hall, Englewood Cliffs, N.J., 1988, pp. 358–390.
17. W. P. Linak and J. O. L. Wendt, *Prog. Energ. Combust. Sci.* **19**, 145, (1993).
18. C. L. Senior, A. F. Sarofim, T. Zeng, J. J. Helble and R. Mamani–Paco, *Fuel. Proc. Technol.* **63**(2–3), 197, (2000).
19. B. K. Gullett, P. M. Lemieux, and J. E. Dunn, *Environ. Sci. Technol.* **28**, 107, (1994).
20. P. M. Lemieux, C. L. Christopher, J. A. Abbott, and K. M. Aldous, *Environ. Sci. Technol.* **34**, 377, (2000).
21. G. H. Rigo, A. J. Chandler, and W. S. Lanier. *The Relationship Between Chlorine in Waste Streams and Dioxin Emissions from Waste Combustor Stacks*, ASME Research Report CRTD-Vol. 36, 1996.
22. J. O. L. Wendt and W. P. Linak, *Combust. Sci. Tech.* **61**, 169, (1988).
23. J. O. L. Wendt, W. P. Linak, and P. M. Lemieux, *Hazardous Waste Hazardous Mater.* **7**, 41, (1990).
24. A. L. Jakeway, A. M. Sterling, V. A. Cundy, C. A. Cook, and A. N. Montestruc. *J. Air & Waste Manage. Assoc.* **45**, 877, (1995).
25. *U.S. Code of Federal Regulations*, Title 40, Part 261, Appendix II, Washington, D.C., July 1991.
26. Ref. 25, Appendix VIII.
27. U.S. Environmental Protection Agency, *Waste: Hazardous Waste Combustion*, http://www.epa.gov/epaoswer/hazwaste/combust.htm, last accessed January 2004.

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