3. COMBUSTION SOURCES OF CDD/CDF: WASTE INCINERATION

Incineration is the destruction of solid, liquid, or gaseous wastes through the application of heat within a controlled combustion system. The purposes of incineration are to reduce the volume of waste that needs land disposal and to reduce the toxicity of the waste, making it more sterile. In keeping with this definition, incinerator systems can be classified by the types of wastes incinerated: municipal solid waste incineration; medical and pathological waste incineration; hazardous waste incineration; sewage sludge incineration; tire incineration; and biogas flaring. Each of these types of incinerators are discussed in this chapter. The purposes of this chapter are to: characterize and describe waste incineration technologies in the United States and to derive estimates of annual releases of CDDs and CDFs into the atmosphere from these facilities for reference years 1987 and 1995.

Combustion research has developed three theories on the mechanisms involved in the emission of CDDs and CDFs from combustion systems: (1) CDD/CDFs can be introduced into the combustor with the feed and pass through the system unchanged, (2) CDD/CDFs can be formed during combustion, or (3) CDD/CDFs can be formed via chemical reactions in the post-combustion portion of the system. The total CDD/CDF emissions are likely to be the net result of all three mechanisms; however, their relative importance is often uncertain. To the extent practical with the available data, the combustors in each source category were divided into classes judged to have similar emission factors. This classification effort attempted to reflect the emission mechanisms described above. The emission mechanisms suggest that the aspects of combustor design and operation that could affect CDD/CDF emissions are furnace design, composition of the waste feed, temperature in the post-combustion zone of the system, and type of air pollution control device (APCD) used to remove contaminants from the flue gases. Therefore, incineration systems that are similar in terms of these factors should have similar CDD/CDF emissions. Accordingly, this chapter proposes classification schemes that divide combustors into a variety of design classes based on these factors. Design class, as used here, refers to the combination of furnace type and accompanying APCD.

3.1. MUNICIPAL SOLID WASTE INCINERATION

As discussed previously, CDD/CDF emission theory suggests that CDD/CDF emissions can be related to several factors, including furnace design, composition of the waste feed, temperature in the post-combustion zone of the system, and type of APCD used to remove contaminants from the flue gases. Accordingly, this chapter proposes a classification scheme that divides municipal solid waste incinerators (MSWIs) into a variety of design classes based on those factors. Some APCDs are operated at different temperatures; therefore, operating temperature is used to define some design classes. Because the theory also suggests that feed can influence CDD/CDF emissions, the proposed furnace classification system distinguishes refused-derived fuel from normal municipal solid waste (MSW). This section begins with a description of the MSWI technology and then proposes the design classification scheme. Using this scheme, the MSWI industry is characterized for the reference years 1987 and 1995. Finally, the procedures for estimating emissions are explained, and results summarized.

3.1.1. Description of Municipal Solid Waste Incineration Technologies

For purposes of this report, MSWI furnace types are divided into three major categories: mass burn, modular, and refuse-derived fuel. Each of these furnace types is described below, followed with a description of the APCDs used with these systems.

Furnace Types

Mass Burn: Historically, this furnace type derived its name because it burned MSW as received (i.e., no preprocessing of the waste was conducted other than removal of items too large to go through the feed system). Today, a number of other furnace types also burn unprocessed waste (as described below). Mass burn furnaces are distinguished from these others because they burn the waste in a single stationary chamber. In a typical mass burn facility, MSW is placed on a grate that moves through the combustor. The 1995 inventory indicates that the combustion capacity of facilities ranges from 90 to 2,700 metric tons of MSW per day. Three subcategories of mass burn (MB) technologies are described below:

- Mass burn refractory-walled (MB-REF) systems represent an older class of MSWIs (generally built in the late 1970s to early 1980s) that were designed only to reduce

the volume of waste in need of disposal by 70 to 90 percent. These facilities usually lacked boilers to recover the combustion heat for energy purposes. In the MB-REF design, the MSW is delivered to the combustion chamber by a traveling grate and/or a ram feeding system. Combustion air in excess of stoichiometric amounts (i.e., more oxygen is supplied than needed for complete combustion) is supplied both below and above the grate.

- Mass burn waterwall (MB-WW) facilities represent enhanced combustion efficiency, as compared with MB-REF incinerators. Although it achieves similar volume reductions, the MB-WW incinerator design provides a more efficient delivery of combustion air, resulting in sustained higher temperatures. Figure 3-1 is a schematic of a typical MB-WW MSWI. The term 'waterwall ' refers to a series of steel tubes, running vertically along the walls of the furnace. The tubes contain water, which when heated by combustion, transfer energy from the heat of combustion to the water. The water reaches boiling temperature, and steam is produced. The steam is then used to drive an electrical turbine generator or for other industrial needs. This transfer of energy is termed 'energy recovery.'

- Mass burn rotary kiln combustors (MB-RC) use a water-cooled rotary combustor, which consists of a rotating combustion barrel configuration mounted at a 15-20^{o} angle of decline. The refuse is charged at the top of the rotating kiln by a hydraulic ram (Donnelly, 1992). Preheated combustion air is delivered to the kiln through various portals. The slow rotation of the kiln (i.e., 10 to 20 rotations/hour) causes the MSW to tumble, thereby exposing more surface area for complete burnout of the MSW. These systems are also equipped with boilers for energy recovery. Figure 3-2 is a schematic of a typical MB-RC MSWI.

Modular Incinerator: This is the second general type of MSWI furnace used in the United States. As with the mass burn type, modular incinerators burn waste without preprocessing. Modular MSWIs consist of two vertically mounted combustion chambers (i.e., a primary and secondary chamber). In the 1995 inventory, modular combustors' combustion capacity ranged from 4 to 270 metric tons/day. The two major types of modular systems, "excess air" and "starved air," are described below.

- The modular excess-air system consists of a primary and secondary combustion chamber, both of which operate with air levels in excess of stoichiometric requirements (i.e., 100 to 250 percent excess air). Figure 3-3 illustrates a typical modular excess air MSWI.

- Starved (or controlled) air is another type of modular system in which air is supplied to the primary chamber at sub-stoichiometric levels. The products of incomplete combustion entrain in the combustion gases that are formed in the primary combustion chamber, then pass into a secondary combustion chamber. Excess air is added to the secondary chamber, and combustion is completed by elevated

temperatures sustained with auxiliary fuel (usually natural gas). The high and uniform temperature of the secondary chamber, combined with the turbulent mixing of the combustion gases, results in low-levels of particulate matter and organic contaminants being formed and emitted. Therefore, many existing modular units lack post-combustion air pollution control devices. Figure 3-4 is a schematic view of a modular starved air MSWI.

Refuse-Derived Fuel (RDF): The third major type of MSWI furnace technology is designed to combust refuse-derived fuel (RDF). RDF is a general term that describes MSW from which relatively noncombustible items are removed, thereby enhancing the combustibility of the MSW. RDF is commonly prepared by shredding, sorting, and separating out metals to create a dense MSW fuel in a pelletized form having a uniform size. Three types of RDF systems are described below.

- The dedicated RDF system burns RDF exclusively. Figure 3-5 shows a typical dedicated RDF using a spreader-stoker boiler. Pelletized RDF is fed into the combustor through a feed chute, using air-swept distributors; this allows a portion of the feed to burn in suspension and the remainder to burn out after falling on a horizontal traveling grate. The traveling grate moves from the rear to the front of the furnace, and distributor settings are adjusted so that most of the waste lands on the rear two-thirds of the grate. This allows more time to complete combustion on the grate. Underfire and overfire air are introduced to enhance combustion, and these incinerators typically operate at 80 to 100 percent excess air. Waterwall tubes, a superheater, and an economizer are used to recover heat for production of steam and/or electricity. The 1995 inventory indicates that dedicated RDF facilities range in total combustion capacity from 227 to 2,720 metric tons/day.

- Cofired RDFs burn both RDF and normal MSW.

- The fluidized-bed RDF (FB-RDF) burns the waste in a turbulent and semi-suspended bed of sand. The MSW may be fed into the incinerator either as unprocessed waste or as a form of RDF. The RDF may be injected into or above the bed through ports in the combustor wall. The sand bed is suspended during combustion by introducing underfire air at a high velocity, hence the term "fluidized." Overfire air at 100 percent stoichiometric requirements is injected above the sand suspension. Waste-fired FB-RDFs typically operate at 30 to 100 percent excess air levels and at bed temperatures around 815°C (1,500°F). A typical FB-RDF is presented as Figure 3-6. Technology has two basic design concepts: (1) a bubbling-bed incineration unit and (2) a circulating-bed incineration unit. The 1995 inventory indicates that fluidized-bed MSWIs have capacities ranging from 184 to 920 metric tons/day. These systems are usually equipped with boilers to produce steam.

Air Pollution Control Devices (APCDs)

MSWIs are commonly equipped with one or more post-combustion APCDs to remove various pollutants prior to release from the stack (e.g., particulate matter, heavy metals, acid gases, and/or organic contaminants) (U.S. EPA, 1992d). These APCDs include:

- Electrostatic precipitator (ESP),
- Fabric filter (FF),
- Dry scrubber (DS),
- Dry sorbent injection (DSI), and
- Wet scrubber (WS)

Electrostatic Precipitator: The ESP is generally used to collect and control particulate matter that evolves during MSW combustion, by introducing a strong electrical field in the flue gas stream; this, in turn, charges the particles entrained in the combustion gases (Donnelly, 1992). Large collection plates receive an opposite charge to attract and collect the particles. CDD/CDF formation can occur within the ESP at temperatures in the range of 150 to about 350°C. As temperatures at the inlet to the ESP increase from 150 to 300°C, CDD/CDF concentrations have been observed to increase by approximately a factor of two for each 30°C increase in temperature (U.S. EPA, 1994f). As temperature increases beyond 300°C, formation rates decline. Although ESPs in this temperature range efficiently remove most particulates and the associated CDD/CDFs, the formation that occurs can result in a net increase in CDD/CDF emissions. This temperature related formation of CDD/CDF within the ESP can be applied to distinguish hot-side ESPs from cold-side ESPs. For purposes of this report, ESPs are classified as follows:

- A cold-side ESP operates at or below 230°C.
- A hot-side ESP operates at an inlet temperature greater than 230°C.

Fabric Filters (FF): FFs are also particulate matter control devices, which remove dioxins associated with particles and any vapors that adsorb to the particles. Six- to 8-inch diameter bags, made from woven fiberglass material, are usually arranged in series. An induction fan forces the combustion gases through the tightly woven fabric. The porosity of the fabric allows the bags to act as filter media and retain a broad range of particles sizes (i.e., down to less than 1 micrometer in diameter). The FF is sensitive to

acid gas; therefore, it is usually operated in combination with spray dryer adsorption of acid gases.

Dry Scrubbers (DS): DSs, also called spray dryer adsorption, involve both the removal of acid gas and particulate matter from the post-combustion gases. By themselves, these units probably have little effect on dioxin emissions. In a typical DS system, hot combustion gases enter a scrubber reactor vessel. An atomized hydrated lime slurry (water plus lime) is injected into the reactor at a controlled velocity (Donnelly, 1992). The hydrated lime slurry rapidly mixes with the combustion gases within the reactor. The water in the hydrated lime slurry quickly evaporates, and the heat of evaporation causes the combustion gas temperature to rapidly decrease. The neutralizing capacity of hydrated lime reduces the combustion gas content of acid gas constituents (e.g., hydrogen chloride gas, and sulfur dioxide gas) by greater than 70 percent. A dry product, consisting of particulate matter and hydrated lime, settles to the bottom of the reactor vessel. DS technology is used in combination with ESPs. The DS reduces ESP inlet temperatures to make a cold-side ESP. DS/FFs have achieved greater than 95 percent reduction and control of CDD/CDFs in MSWI emissions (U.S. EPA, 1992d).

Dry Sorbent Injection (DSI): DSI is used to reduce acid gas emissions. By themselves, these units probably have little effect on dioxin emissions. DSI involves the injection of dry hydrated lime or soda ash either directly into the combustion chamber or into the flue duct of the hot post-combustion gases. In either case, the reagent reacts with and neutralizes the acid gas constituents (Donnelly, 1992).

Wet Scrubber (WS): WS devices are designed for acid gas removal, and are more common to MSWIs in Europe than in the United States. They should help reduce emissions of dioxin in both vapor and particle forms. WS devices consist of two-stage scrubbers. The first stage removes hydrogen chloride (HCl), and the second stage removes sulfur dioxide (SO_2) (Donnelly, 1992). Water is used to remove the HCl, and caustic or hydrated lime is added to remove SO_2 from the combustion gases.

In addition to the APCDs described above, some less common types are also used in some MSWIs. An example is the Electro Granular Bed (EGB), which consists of a packed bed of activated carbon. An electric field is passed through the packed bed; particles entrained in the flue gases are given a negative charge, and the packed bed is given a positive charge. EGB systems function much like an ESP. Particulate matter is

collected within the bed; therefore, they will remove dioxins associated with collected particles and any vapors that adsorb to the particles. Only one facility in the United States currently employs the EGB system, a fluidized bed-RDF MSWI.

Classification Scheme

Based on the array of MSWI technologies described above, a classification system for deriving CDD/CDF emission estimates was developed. As discussed earlier, it is assumed that facilities with common design and operating characteristics have a similar potential for CDD/CDF emissions. The MSWIs operating in 1987 and 1995 were divided according to the eight furnace types and seven APCDs described above. This resulted in 17 design classes in 1987 and 40 design classes in 1995. Because fewer types of APCDs were used in 1987 than in 1995, fewer design classes are needed for estimating emissions. This taxonomy is summarized in Figures 3-7 and 3-8.

3.1.2. Characterization of MSWI Facilities in Reference Years 1995 and 1987

Table 3-1 lists by design/APCD type, the number of facilities and activity level (kg MSW incinerated per year) for MSWIs in the reference year 1995. A similar inventory is provided for reference year 1987 in Table 3-2. This information was derived from four reports: U.S. EPA (1987b), Systems Applications International (1995), Taylor and Zannes (1996), and Solid Waste Technologies (1994). In general, these studies collected the information via telephone interviews with the plant operators.

Using Tables 3-1 and 3-2, a number of comparisons can be made between the two reference years:

- The number of facilities stayed about the same (113 in 1987 and 130 in 1995), but the amount of MSW incinerated more than doubled (13.8 billion kg in 1987 and 28.8 billion kg in 1995).
- The dominant furnace technology shifted from modular in 1987 (57 units and 1.4 billion kg) to mass burn waterwall facilities in 1995 (57 units and 17 billion kg).
- The dominant APCD technology shifted from hot-sided ESPs in 1987 (54 units and 11 billion kg) to fabric filters in 1995 (55 units and 16 billion kg).
- The use of hot-sided ESPs dropped from 54 facilities in 1987 (11 billion kg) to 16 facilities in 1995 (2.2 billion kg).
- The number of uncontrolled facilities dropped from 38 in 1987 (0.6-billion kg) to 10 facilities in 1995 (0.2 billion kg).

3.1.3. Estimation of CDD/CDF Emissions from MSWIs

Compared to other CDD/CDF source categories, MSWIs have been more extensively evaluated for CDD/CDF emissions. Within the context of this report, adequate emission testing for CDD/CDFs were available for 11 of the 113 facilities in the 1987 inventory and 27 of the 130 facilities in the 1995 inventory. Nationwide CDD/CDF air emissions from MSWIs were estimated using a three-step process as described below.

Step 1. Estimation of emissions from all stack tested facilities. The EPA stack testing method (EPA Method 23) produces a measurement of CDD/CDF in units of mass concentration of CDD/CDF (i.e., nanograms per dry standard cubic meter of combustion gas [ng/dscm]) at standard temperature and pressure (20°C and 1 atmosphere), and adjusted to a measurement of 7 percent oxygen in the flue gas (U.S. EPA, 1995b). This concentration is assumed to represent conditions at the point of release from the stack into the air. Equation 3-1 below was used to derive annual emission estimates for each tested facility:

$$E_{TEQ} = \frac{C \times V \times CF \times H}{10^9 \text{ ng/g}} \qquad \text{(Eqn. 3-1)}$$

Where:

E_{TEQ}	=	Annual TEQ emission (g/yr)
C	=	Combustion flue gas TEQ concentration (ng/dscm) (20°C, 1 atm; adjusted to 7% O_2)
V	=	Volumetric flow rate of combustion flue gas (dscm/hour) (20°C, 1 atm; adjusted to 7% O_2)
CF	=	Capacity factor, fraction of time that the MSWI operates (i.e., 0.85)
H	=	Total hours in a year (8,760 hr/yr)

After calculating annual emissions for each tested facility, the emissions were summed across all tested facilities for each reference year. [Note: Many of the emission tests do not correspond exactly to these 2 years. In these cases, the equipment conditions present at the time of the test were compared to those during the reference year to determine their applicability.]

Step 2. Estimation of emissions from all non-tested facilities. This step involves multiplying the emission factor and annual activity level for each MSWI design class and then summing across classes. The activity levels for reference years 1995 and 1987 are summarized in Tables 3-1 and 3-2, respectively. The emission factors were derived by averaging the emission factors across each tested facility in a design class. The emission factor for each facility was calculated using the following equation:

$$EF_{mswi} = \frac{C \times F_v}{I_w} \qquad \text{(Eqn. 3-2)}$$

Where:

EF_{mswi} = Emission factor, average ng TEQ per kg of waste burned
C = TEQ or CDD/CDF concentration in flue gases (ng TEQ/dscm) (20°C, 1 atm; adjusted to 7% O_2)
F_v = Volumetric flue gas flow rate (dscm/hr) (20°C, 1 atm; adjusted to 7% O_2)
I_w = Average waste incineration rate (kg/hr)

Example: A mass burn waterwall MSWI equipped with cold-sided ESP.

Given:

C = 10 ng TEQ/dscm (20°C, 1 atm; adjusted to 7% O_2)
F_v = 40,000 dscm/hr (20°C, 1 atm; adjusted to 7% O_2)
I_w = 10,000 kg MSW/hr

$$EF_{MBWW} = \frac{10 \text{ ng}}{\text{dscm}} \times \frac{40{,}000 \text{ dscm}}{\text{hr}} \times \frac{\text{hr}}{10{,}000 \text{ kg}}$$

$$EF_{MBWW} = \frac{40 \text{ ng TEQ}}{\text{kg MSW burned}}$$

EPA was not able to obtain engineering test reports of CDD/CDF emissions for a number of design classes. In these cases, the above procedure could not be used to derive emission factors. Instead, the emission factors of the tested design class that was judged most similar in terms of dioxin control was assumed to apply to the untested class. The following logic was used to make this decision:

1. The tested APCDs for the furnace type of the untested class were reviewed to see if any operated at a similar temperature.
2. If any operated at similar temperatures, the one with most similar technology was assumed to apply.
3. If none operated at a similar temperature, then the most similar furnace type with same control device was assumed to apply.

Table 3-3 lists all design categories with no tested facilities and shows the class with tested facilities that was judged most similar.

It should be understood that the emission factors for each design class are the same for both reference years. This is because the emission factor is determined only by the design and operating conditions and is independent of the year of the test.

Step 3. Sum emissions from tested and untested facilities. This step simply involves summing emissions from all tested and untested facilities. This process is shown in Tables 3-4 and 3-5 for the reference years 1995 and 1987, respectively. The tables are organized by design class and show separately the emission estimates for the tested and untested facilities. The calculation of emissions from untested facilities is broken out to show the activity level and emission factor for each design class.

3.1.4. Summary of CDD/CDF (TEQ) Emissions from MSWIs for 1995 and 1987

The activity level estimates (i.e., the amount of MSW that is annually combusted by the various MSWI technologies) are given a high confidence rating for both 1987 (i.e., 13.8 billion kg of waste) and 1995 (i.e., 28.8 billion kg of waste). For both years, comprehensive surveys of activity levels were conducted by independent sources on virtually all facilities (U.S. EPA, 1987b; Systems Application International, 1995; Taylor and Zannes, 1996; Solid Waste Technologies, 1994).

The emission factor estimates are given a medium confidence rating for both 1987 and 1995. A moderate fraction of the facilities were tested in both years: 11 of 113 facilities in 1987 (10 percent), and 27 of 130 facilities (21 percent) in 1995. Moreover, the tested facilities represent 21 and 27 percent of the total activity level of operating MSWIs in 1987 and 1995, respectively. These tests represent most of the design

categories identified in this report. The emission factors were developed from emission tests that followed standard EPA protocols, used strict QA/QC procedures, and were well documented in engineering reports. Because all tests were conducted under normal operating conditions, some uncertainty exists about the magnitude of emissions that may occur during other conditions (i.e., upset conditions, start-up and shut-down).

These confidence ratings produce an overall medium confidence rating in the annual emission estimates of 7,915 g I-TEQ_{DF} (8,877 g TEQ_{DF}-WHO_{98}) in 1987 and 1,100 g I-TEQ_{DF} (1,250 g TEQ_{DF}-WHO_{98}) in 1995.

3.1.5 Congener Profiles of MSWI Facilities

The air emissions from MSWIs contain a mixture of CDD and CDF congeners. These mixtures can be translated into what are termed 'congener profiles,' which represent the distribution of total CDDs and CDFs present in the mixture. A congener profile may serve as a signature of the types of CDDs and CDFs associated with particular MSWI technology and APCD. Figure 3-9 is a congener profile of a mass-burn waterwall MSWI equipped with a dry scrubber and fabric filter (i.e., the most common type of MSWI and APCD design in use today). This congener profile indicates that OCDD dominates CDD/CDF emissions and that every toxic CDD/CDF congener is detected in the emissions.

3.1.6 Estimated CDD/CDFs in MSWI Ash

Ash from MSWIs is required to be disposed of in permitted landfills from which releases to the general environment are controlled. For background purposes, however, some information is presented below about the quantities of CDD/CDFs in ash from MSWIs.

An estimated 7 million metric tons of total ash (bottom ash plus fly ash) were generated by MSWIs in 1992 (telephone conversation between J. Loundsberry, U.S. EPA Office of Solid Waste, and L. Brown, Versar, Inc., on February 24, 1993). U.S. EPA (1991b) indicated that 2 to 5 million metric tons of total ash were produced annually in the late 1980s from MSWIs, with fly ash comprising 5 to 15 percent of the total. U.S. EPA (1990c) reported the results of analyses of MSWI ash samples for CDDs and CDFs. Ashes from five state-of-the-art facilities located in different regions of the United States were analyzed for all 2,3,7,8-substituted CDDs and CDFs. The TEQ levels in the ash (fly

ash mixed with bottom ash) ranged from 106 to 466 ng I-TEQ_{DF}/kg, with a mean value of 258 ng I-TEQ_{DF}/kg. CDD/CDF levels in fly ash are generally much higher than in bottom ash. For example, Fiedler and Hutzinger (1992) reported levels of 13,000 ng I-TEQ_{DF}/kg in fly ash.

In another study (Washington, 1998), CDD/CDF congener data were reported for ash and other solid residuals from three municipal incinerators (Fort Lewis, Bellingham [municipal plus medical wastes], and Spokane). The data were compiled and evaluated to determine a total I-TEQ concentration and loading. Non-detect values were included as either zero, ½ DL, or at the DL. The results were as follows, assuming that non-detect values were at zero concentration:

Location	Type of Residual	T-TEQ (μg/kg)	I-TEQ (mg/day)
Ft. Lewis	Bottom Ash Fly Ash	0.00 4.98	0.00 0.76
Bellingham	Mixed Ash (avg. of 3 tests)	0.038	1.14
Spokane	Mixed Ash Fly Ash Bottom Ash	0.163 0.51 0.0001	38.0 24.3 0.02

In Shane (1990), five municipal incinerator ashes were analyzed for a number of constituents including CDDs (not CDFs) and PCBs. For dioxins, three of the incinerators were at non-detectable levels (detection limit of 1 μg/kg). The other two incinerators had detectable levels of five CDD congener groups. (No analyses were reported for individual congeners.) The average for those two units were:

TCDD	26 μg/kg
PeCDDs	59 μg/kg
HxCDDs	53 μg/kg
HpCDDs	25 μg/kg
OCDDs	12 μg/kg

These levels were much higher that those reported in U.S. EPA (1990c).

For PCBs, the five sets of ashes were analyzed for 10 congener groups. All groups were detected for one of the incinerators. However, the other four incinerators contained little or no octa-, nona-, or deca- congeners. The average PCB concentration (all congener groups) for the five incinerators was 216 μg/kg, with a range of 99-322 μg/kg.

No generation rates of the ashes were given in Shane (1990). Therefore, the measured concentrations cannot be readily converted to quantities of CDDs or PCBs. The ashes from each of the five incinerators were disposed of in multiple fashions. For two of the incinerators, the ash was sent to metal recovery and also landfilled. For a third, the fly ash was sold. For a fourth, the ashes were only landfilled. For the fifth, the ashes were used in road building and also landfilled. For those incinerators with more than one ash disposition, no breakdown was given of how much went to each location. There were 15 other incinerators discussed in Shane (1990). Thirteen of them disposed of their ash exclusively in landfills, and the other two partially disposed of their ash in landfills.

Table 7 of Clement (1988) presented 13 data sets for CDD/CDF congener groups for a municipal incinerator ash. The average data for each congener group and the ranges of each group are given in Table 3-6. No data were presented in Clement (1988) for individual congeners, nor were there data for ash quantities.

In Table 3-3 of U.S. EPA (1987a), there were data stating that ashes from three incinerators (one in North America, one in Europe, and one in Japan) had mean CDD concentrations of 363, 588, and 2.6 μg/kg, respectively. The ranges of those data were from <0.5 to 3.537 μg/kg. Similarly, for CDFs, the respective mean concentrations for the first two incinerators were 923 and 288 μg/kg. The third incinerator was not reported. The CDF range for the two incinerator ashes was <0.5 to 1,770 μg/kg. No data were given for individual congeners, nor were there any data for quantities of the ashes.

In Table 1 of Lahl (1991), data were presented for the concentrations of total CDDs and for total CDFs for the ash from an electrostatic precipitator from a municipal incinerator. Data were reported for summer sampling and for winter sampling. The total CDDs in the summer were 140.46 μg/kg, and for the winter were 86.00 μg/kg. The total CDFs in the summer were 54.97 μg/kg, and for the winter were 73.85 μg/kg. No data

were given for individual congeners, nor was there information about the quantity of precipitator ash generated. It was assumed that the data were not for TEQs.

In Table 3-11 of U.S. EPA (1987a), a wire reclamation incinerator was reported to have 0.41 μg/kg of CDDs and 11.6 μg/kg of CDFs in fly ash from its "stack" emissions. For the same incinerator, the "furnace" ash concentrations were reported as 0.58 μg/kg CDDs and 0.73 μg/kg CDFs. Again, no data were given for individual congeners, nor were there any data for quantities of the ashes.

Data from the aforementioned sources have been compiled in Table 3-7 for comparison purposes. Annual TEQ amounts were estimated by multiplying the mean TEQ total ash concentration by the estimated amount of MSWI ash generated annually (approximately 7 million metric tons in 1995 and 5 million metric tons in 1987). Where possible, ash quantities were broken down into fly ash and/or bottom ash categories. Fly ash is assumed to be 10% of the total ash and bottom ash is assumed to be 90% of the total ash.

Each of the five facilities sampled in U.S. EPA (1990c) had companion ash disposal facilities equipped with leachate collection systems or some means of collecting leachate samples. Leachate samples were collected and analyzed for each of these systems. Detectable levels were only found in the leachate at one facility (3 ng I-TEQ_{DF}/L); the only detectable congeners were HpCDDs, OCDD, and HpCDFs.

3.1.7 Recent EPA Regulatory Activities

On December 19, 1995, EPA promulgated CDD/CDF emission standards for all existing and new MSWI units at facilities with aggregate combustion capacities greater than 35 metric tons per day (Federal Register, 1995e). In response to a court remand, the regulations were subsequently amended to remove small MWC units (i.e., units with capacities ranging from 35 to 225 kkg/day) (Federal Register, 1997c). The specific emission standards (expressed as ng/dscm of total CDD/CDF - based on standard dry gas corrected to 7 percent oxygen) are a function of the size, APCD configuration, and age of the facility as listed below:

1995 Emission standard (ng total CDD/CDF/dscm)	Facility age, size, and APCD
60	• Existing; >225 metric tons/day; ESP-based APCD
30	• Existing; >225 metric tons/day; non-ESP-based APCD
13	• New; >225 metric tons/day

EPA reproposed emission standards for small MWCs (defined as units with capacities of between 32 and 224 kkg/day) on August 30, 1999 (Federal Register, 1999c). The proposed emission standard is 125 ng total CDD/CDF per dscm at 7 percent oxygen.

States have up to 3 years from promulgation of the Federal standards to submit revised State Implementation Plans to EPA for approval. Once approved, States have the primary responsibility to implement the new standards. EPA's Office of Air Quality Planning and Standards (OAQPS) estimates that the full compliance by all MSWIs with the 1995 standards and 1999 proposed standards will result in an annual emission of about 12 g I-TEQ_{DF}/yr (U.S. EPA, 2000a).

3.2. HAZARDOUS WASTE INCINERATION

Hazardous waste incineration (HWI) is the controlled pyrolysis and/or oxidation of potentially dangerous liquid, gaseous and solid waste. HWI is one technology used to manage hazardous waste under the Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Superfund) programs. As described below, hazardous wastes are burned in a variety of situations and are covered in a number of different sections in this report.

- Much of the hazardous waste is burned in facilities dedicated to burning hazardous waste. Most of these dedicated facilities are located on-site at chemical manufacturing facilities and only burn waste associated with their on-site industrial operations. Hazardous waste is also burned at dedicated facilities located off-site from manufacturing facilities and accept waste from multiple sources. These fixed location facilities dedicated to burning hazardous waste at both on- and off-site locations are addressed in Sections 3.2.1 to 3.2.4.

- Hazardous waste is also burned in industrial boilers and furnaces that are permitted to burn the waste as supplemental fuel. These facilities have significantly different

furnace designs and operations than dedicated HWIs; therefore, they are discussed in Section 3.2.5.

- A number of cement kilns and lightweight aggregate kilns are also permitted to burn hazardous waste as auxiliary fuel; these are discussed separately in Section 5.1.

- Mobile HWIs are typically used for site cleanup at Superfund sites and operate for a limited duration at any given location. These units are mobile in the sense that they can be transported from one location to another. Due to the transitory nature of these facilities, they are not included in this inventory at this time.

The following subsections review the types of HWI technologies commonly in use in the United States, and present the derivation of emissions estimates of CDD/CDFs from all facilities operating in 1995 and 1987.

3.2.1. Furnace Designs for Hazardous Waste Incinerators

The four principal furnace designs employed for the combustion of hazardous waste in the United States are: rotary kiln, liquid injection, fixed hearth, and fluidized-bed incinerators (Dempsey and Oppelt, 1993). The majority of commercial operations are of the rotary kiln incinerator type. On-site (noncommercial) HWI technologies are an equal mix of rotary kiln and liquid injection facilities, with a few additional fixed hearths and fluidized bed operations (U.S. EPA, 1996h). Each of these HWI technologies is discussed below:

Rotary Kiln HWI: Rotary kiln incinerators consist of a rotary kiln, coupled with a high temperature afterburner. Because these are excess air units designed to combust hazardous waste in any physical form (i.e., liquid, semi-solid, or solid), rotary kilns are the most common type of hazardous waste incinerator used by commercial off-site operators. The rotary kiln is a horizontal cylinder lined with refractory material. Rotation of the cylinder on a slight slope provides for gravitational transport of the hazardous waste through the kiln (Buonicore, 1992a). The tumbling action of the rotating kiln causes mixing and exposure of the waste to the heat of combustion, thereby enhancing burnout. Solid and semi-solid wastes are loaded into the top of the kiln by an auger or rotating screw. Fluid and pumpable sludges and wastes are typically introduced into the kiln through a water-cooled tube. Liquid hazardous waste is fed directly into the kiln through a burner nozzle. Auxiliary fuel (natural gas or oil) is burned in the kiln chamber at start-up

to reach elevated temperatures. The typical heating value of hazardous waste (i.e., 8,000 Btu/kg) is sufficient to sustain combustion without auxiliary fuel (U.S. EPA, 1996h). The combustion gases emanating from the kiln are passed through a high temperature afterburner chamber to more completely destroy organic pollutants entrained in the flue gases. Rotary kilns can be designed to operate at temperatures as high as 2,580°C, but more commonly operate at about 1,100°C.

Liquid Injection HWI: Liquid injection incinerators (LIIs) are designed to burn liquid hazardous waste. These wastes must be sufficiently fluid to pass through an atomizer for injection as droplets into the combustion chamber. The LIIs consist of a refractory-lined steel cylinder mounted either in a horizontal or vertical alignment. The combustion chamber is equipped with one or more waste burners. Because of the rather large surface area of the atomized droplets of liquid hazardous waste, the droplets quickly vaporize. The moisture evaporates, leaving a highly combustible mix of waste fumes and combustion air (U.S. EPA, 1996h). Secondary air is added to the combustion chamber to complete the oxidation of the fume/air mixture.

Fixed Hearth HWI: Fixed hearths are starved air or pyrolytic incinerators. Waste is ram-fed into the primary chamber and incinerated below stoichiometric requirements (i.e., at about 50 to 80 percent of stoichiometric air requirements). The resulting smoke and pyrolytic combustion products are then passed though a secondary combustion chamber where relatively high temperatures are maintained by the combustion of auxiliary fuel. Oxygen is introduced into the secondary chamber to promote complete thermal oxidation of the organic molecules entrained in the gases.

Fluidized-bed HWI: The fourth hazardous waste incineration technology is the fluidized-bed incinerator, which is similar in design to that used in municipal solid waste incineration. (See Section 3.1.) In this configuration, a layer of sand is placed on the bottom of the combustion chamber. The bed is preheated by underfire auxiliary fuel at startup. During combustion of auxiliary fuel at start-up, the hot gases are channeled through the sand at relatively high velocity, and the turbulent mixing of combustion gases and combustion air causes the sand to become suspended (Buonicore, 1992a). This takes on the appearance of a fluid medium, hence the incinerator is termed a 'fluidized bed' combustor The incinerator is operated below the melting point temperature of the bed material. Typical temperatures of the fluid medium are within the range of 650 to 940°C.

A constraint on the types of waste burned is that the solid waste particles must be capable of being suspended within the furnace. When the liquid or solid waste is combusted in the fluid medium, the exothermic reaction causes heat to be released into the upper portion of the combustion chamber. The upper portion is typically much larger in volume than the lower portion, and temperatures can reach 1,000°C (Buonicore, 1992a). This high temperature is sufficient to combust volatilized pollutants emanating from the combustion bed.

3.2.2. APCDs for Hazardous Waste Incinerators

Most HWIs use APCDs to remove undesirable components from the flue gases that evolved during the combustion of the hazardous waste. These unwanted pollutants include suspended ash particles (particulate matter or PM), acid gases, metal, and organic pollutants. The APCD controls or collects these pollutants and reduces their discharge from the incinerator stack to the atmosphere. Levels and kinds of these combustion byproducts are highly site-specific, depending on factors such as waste composition and incinerator system design and operating parameters (e.g., temperature and exhaust gas velocity). The APCD is typically comprised of a series of different devices that work together to clean the exhaust combustion flue gas. Unit operations usually include exhaust gas cooling, followed by particulate matter and acid gas control.

Exhaust gas cooling may be achieved using a waste heat boiler or heat exchanger, mixing with cool ambient air, or injection of a water spray into the exhaust gas. A variety of different types of APCDs are employed for the removal of particulate matter and acid gases. Such devices include: wet scrubbers (such as venturi, packed bed, and ionizing systems), electrostatic precipitators, and fabric filters (sometimes used in combination with dry acid gas scrubbing). In general, the control systems can be grouped into the following three categories: wet, dry, and hybrid wet/dry systems. The controls for acid gases (either dry or wet systems) cause temperatures to be reduced preceding the control device. This impedes the extent of formation of CDDs and CDFs in the post-combustion area of the typical HWI. It is not unusual for stack concentrations of CDD/CDFs at a particular HWI to be in the range of 1 to 100 ng CDD/CDF/dscm (Helble, 1993), which is low in comparison to other waste incineration systems. The range of total CDD/CDF flue gas concentrations measured in the stack emissions of HWIs during trial burns across the

class of HWI facilities, however, has spanned four orders of magnitude (ranging from 0.1 to 1,600 ng/dscm) (Helble, 1993). The APCD systems are described below:

- **Wet Systems:** A wet scrubber is used for both particulate and acid gas control. Typically, a venturi scrubber and packed-bed scrubber are used in a back-to-back arrangement. Ionizing wet scrubbers, wet electrostatic precipitators, and innovative venturi-type scrubbers may be used for more efficient particulate control. Wet scrubbers generate a wet effluent liquid wastestream (scrubber blowdown), are relatively inefficient at fine particulate control compared to dry control techniques, and have equipment corrosion concerns. However, wet scrubbers do provide efficient control of acid gases and have lower operating temperatures (compared with dry systems), which may help control the emissions of volatile metals and organic pollutants.
- **Dry Systems:** In dry systems, a fabric filter or electrostatic precipitator (ESP) is used for particulate control. A fabric filter or ESP is frequently used in combination with dry scrubbing for acid gas control. Dry scrubbing systems, in comparison with wet scrubbing systems, are inefficient in controlling acid gases.
- **Hybrid Systems:** In hybrid systems, a dry technique (ESP or fabric filter) is used for particulate control, followed by a wet technique (wet scrubber) for acid gas control. Hybrid systems have the advantages of both wet and dry systems (lower operating temperature for capture of volatile metals, efficient collection of fine particulate, efficient capture of acid gases), while avoiding many of the individual disadvantages. In some hybrid systems, known as "zero discharge systems," the wet scrubber liquid is used in the dry scrubbing operation, thus minimizing the amount of liquid byproduct waste.
- **Uncontrolled HWIs:** Facilities that do not use any air pollution control devices fall under a separate and unique category. These are primarily liquid waste injection facilities, which burn low ash and chlorine content wastes; therefore, they are low emitters of PM and acid gases.

3.2.3. Estimation of CDD/CDF Emission Factors for Hazardous Waste Incinerators

For purposes of estimating emission factors, this document considers subdividing the combustors in each source category into design classes judged to have similar potential for CDD/CDF emissions. As explained below, it was decided not to subdivide dedicated HWIs.

Combustion research has identified three mechanisms involved in the emission of CDD/CDFs from combustion systems: (1) CDD/CDFs can be introduced into the combustor with the feed and pass through the system not completely burned/destroyed; (2) CDD/CDFs can be formed by chemical reactions inside the combustion chamber; and (3) CDD/CDFs can be formed by chemical reactions outside the combustion chamber. The total CDD/CDF emissions are likely to be the net result of all three mechanisms; however, the relative importance of the mechanisms can vary among source categories. In the case of HWIs, the third mechanism (i.e., post-combustion formation) is likely to dominate, because HWIs are typically operated at high temperatures and long residence times, and most have sophsiticated real-time monitoring and controls to manage the combustion process. Therefore, any CDD/CDFs present in the feed or formed during combustion are likely to be destroyed before exiting the combustion chamber. Consequently, for purposes of generating emission factors, it was decided not to subdivide this class on the basis of furnace type.

Emissions resulting from the post-combustion formation in HWIs can be minimized through a variety of technologies:

- **Rapid Flue Gas Quenching**: The use of wet and dry scrubbing devices to remove acid gases usually results in the rapid reduction of flue gas temperatures at the inlet to the PM APCD. If temperature is reduced below 200˚C, the low-temperature catalytic formation of CDD/CDFs is substantially retarded.
- **Use of Particulate Matter (PM) Air Pollution Control Devices**: PM control devices can effectively capture condensed and adsorbed CDD/CDFs that are associated with the entrained particulate matter (in particular, that which is adsorbed on unburned carbon containing particulates).

- **Use of Activated Carbon**: Activated carbon injection is used at some HWIs to collect (sorb) CDD/CDFs from the flue gas. This may be achieved using carbon beds or by injecting carbon and collecting it in a downstream PM APCD.

All of these approaches appear very effective in controlling dioxin emissions at dedicated HWIs, and insufficient emissions data are available to generalize about any minor differences. Consequently, for purposes of generating emission factors, it was decided not to subdivide this class on the basis of APCD type.

EPA compiled a data base summarizing the results of stack testing for CDDs and CDFs at 17 HWIs (U.S. EPA, 1996c). Most facilities were tested between 1993 and 1996. For purposes of this report, CDD/CDF emission factors were estimated based on the results of the emission tests contained in this data base. The breakdown of furnace types of tested HWI facilities is as follows: 10 rotary kiln incinerators, 4 liquid injection incinerators, 1 fluidized-bed incinerator, and 2 fixed-bed.

As stated earlier, EPA/ORD decided not to subclassify the dedicated HWI designs for purposes of deriving an emission factor (EF). Instead, the emission factor was derived as an average across all 17 tested facilties. First, an average emission factor was calculated for each of 17 HWIs with Equation 3-3.

$$EF_{hwi} = \frac{C \times F_v}{I_w} \qquad \text{(Eqn. 3-3)}$$

Where:

EF_{hwi} = Emission factor (average ng TEQ per kg of waste burned)
C = TEQ or CDD/CDF concentration in flue gases (ng TEQ/dscm) (20°C, 1 atm; adjusted to 7% O_2)
F_v = Volumetric flue gas flow rate (dscm/hr) (20°C, 1 atm; adjusted to 7% O_2)
I_w = Average waste incineration rate (kg/hr)

After developing average emission factors for each HWI, the overall average congener-specific emission factor was derived for all 17 tested HWIs using Equation 3-4.

$$EF_{avgHWI_{n=1-17}} = (EF_{HWI_1} + EF_{HWI_2} + EF_{HWI_3} + \ldots\ldots + EF_{HWI_{17}}) / N \qquad \text{(Eqn. 3-4)}$$

Where:

EF_{HWI} = Average emission factor for the 17 tested HWIs, (ng/kg)
N = Number of tested facilities (i.e., 17)

Table 3-8 presents the average emission factors developed for specific congeners, total CDDs/CDFs, and TEQs for the tested HWIs. The average congener emission profile for the 17 tested HWIs are presented in Figure 3-10. The average I-TEQ_{DF} and TEQ_{DF}-WHO_{98} emission factors for the 17 tested HWIs are 3.83 ng I-TEQ_{DF}/kg of waste feed and 3.88 ng TEQ_{DF}-WHO_{98}/kg of waste feed (assuming not detected values are zero). The available data did not support development of different emission factors for the two reference years, 1987 and 1995.

3.2.4. Emission Estimates for Hazardous Waste Incinerators

Although emissions data were available for 10 percent of the HWIs (i.e., 17 of 162 have been tested), the emission factor estimates are assigned a medium confidence rating due to uncertainties resulting from:

- *Variability of the waste feeds*. The physical and chemical composition of the waste can vary from facility to facility and even within a facility. Consequently, CDD/CDF emissions measured for one feed may not be representative of other feeds.

- *Trial burns*. Much of the CDD/CDF emissions data were collected during trial burns, which are required as part of the RCRA permitting process and are used to establish Destruction Rated Efficiency (DRE) of principal hazardous organic constituents in the waste. During trial burns, a prototype waste is burned, which is intended to maximize the difficulty in achieving good combustion. For example, chlorine, metals, and organics may be added to the waste. The HWI may also be operated outside normal operating conditions. The temperature of both the furnace and the APCD may vary by a wide margin (high and low temperatures), and the waste feed system may be increased to maximum design load. Accordingly, it is uncertain how representative the CDD/CDF emissions measured during the trial burn will be of emissions during normal operating conditions.

Dempsey and Oppelt (1993) estimated that up to 1.3 million metric tons of hazardous waste were combusted in HWIs during 1987. EPA estimated that 1.5 million metric tons of hazardous waste were combusted each year in the early 1990s in HWIs (Federal Register, 1996b). This activity level estimate for 1995 is assigned a high confidence rating, because it is based on a review by EPA of the various studies and surveys conducted in the 1990s to assess the quantity and types of hazardous wastes

being managed by various treatment, storage, and disposal facilities. A confidence rating of medium is assigned to the activity level estimate for 1987.

The annual TEQ emissions for the reference years 1995 and 1987 were estimated using Equation 3-5.

$$E_{HWI} = EF_{HWI} \times A_{HWI} \qquad \text{(Eqn. 3-5)}$$

Where:

E_{HWI} = Annual emissions from all HWIs, tested and non-tested (g TEQ/yr)
EF_{HWI} = Mean emission factor for HWIs (ng TEQ/kg of waste burned)
A_{HWI} = Annual activity level of all operating HWIs (million metric tons/yr)

Applying the average TEQ emission factors for dedicated HWIs (3.83 ng I-TEQ_{DF}/kg and 3.88 ng TEQ_{DF}-WHO_{98}/kg waste) to these production estimates yields estimated emissions of 5.7 g I-TEQ_{DF} (or 5.8 g TEQ_{DF}-WHO_{98}) in 1995 and 5.0 g TEQ (I-TEQ_{DF} or TEQ_{DF}-WHO_{98}) in 1987 for HWIs. The medium confidence rating assigned to the emission factor, combined with the medium confidence rating for the 1995 activity level and medium confidence rating for the 1987 activity level, yields an overall medium confidence rating for both years.

3.2.5. Recent EPA Regulatory Activities

EPA/OSW has also developed estimates of the CDD/CDF emissions from HWIs as part of the development of the Hazardous Waste Combustors Rule (Federal Register, 1999b). Like ORD, OSW also decided not to subdivide the HWIs on the basis of design. Instead of an emission factor approach, OSW used an imputation method to estimate emissions at untested facilities. This procedure involved randomly selecting measured CDD/CDF flue gas concentrations (ng/dscm) from the pool of tested HWI facilities and assigning them to the untested facilities. With this procedure, all non-tested HWIs have an equal chance of being assigned any flue gas concentration from the pool of measured values. The flue gas concentrations were combined with flue gas flow rates for each facility to estimate the emission rate. Using this approach, EPA/OSW estimated that I-TEQ_{DF} emissions in 1997 were 24.8 grams and that the emissions would be reduced to

3.5 g after full implementation of the rule. A key difference in these approaches is that ORD uses waste feed rate directly in the calculation of emissions and the OSW approach is independent of waste feed rate. Both procedures are reasonable ways to deal with the broad range of uncertainties and both yield similar emission estimates. ORD has not identified any inherent advantage of one approach over the other and elected to use the emission factor approach primarily because it is consistent with the methods used in this document to characterize CDD/CDF emissions from all other source categories.

3.2.6. Industrial Boilers and Furnaces Burning Hazardous Waste

In 1991, EPA established rules that allow the combustion of some liquid hazardous waste in industrial boilers and furnaces (Federal Register, 1991c). These facilities typically burn oil or coal for the primary purpose of generating electricity. Liquid hazardous waste can only be burned as supplemental (auxiliary) fuel, and usage is limited by the rule to no more than 5 percent of the primary fuels. These facilities typically use an atomizer to inject the waste as droplets into the combustion chamber and are equipped with particulate and acid gas emission controls. In general, they are sophisticated, well controlled facilities, which achieve good combustion.

The national data base contains congener-specific emission concentrations for two tested boilers burning liquid hazardous waste as supplemental fuel. The average congener and congener group emission profiles for the industrial boiler data set are presented in Figure 3-11. The average congener and TEQ emission factors are presented in Table 3-8. The limited set of emissions data prevented subdividing this class for the purpose of deriving an emission factor. The equation used to derive the emission factor is the same as Equation 3-4 above. The average TEQ emission factor for the two industrial boilers is 0.64 ng I-TEQ_{DF}/kg of waste feed (or 0.65 ng TEQ_{DF}-WHO_{98}/kg of waste feed). These emission factors are assigned a low confidence rating, because they reflect testing at only 2 of the 136 hazardous waste boilers/furnaces.

Dempsey and Oppelt (1993) estimated that approximately 1.2 billion kg of hazardous waste were combusted in industrial boilers/furnaces in 1987. EPA estimates that each year in the early 1990s approximately 0.6 billion kg of hazardous waste were combusted in industrial boilers/furnaces (Federal Register, 1996b). It is possible that cement kilns and lightweight aggregate kilns burning hazardous waste were included in

this estimate by Dempsey and Oppelt for 1987; the estimate for 1995 does not appear to include these hazardous waste burning kilns. This activity level estimate for 1995 is assigned a medium confidence rating, because it was based on a review by EPA of the various studies and surveys conducted in the 1990s to assess the quantity and types of hazardous wastes being managed by various treatment, storage, and disposal facilities. A confidence rating of low is assigned to the estimated activity level for 1987. The 1987 estimate was largely based on a review of State permits (Dempsey and Oppelt,1993).

Equation 3-5, used to calculate annual TEQ emissions for dedicated HWIs, was also used to calculate annual TEQ emissions for industrial boilers/furnaces. Multiplying the average TEQ emission factors by the total estimated kg of liquid hazardous waste burned in 1995 and 1987 yields annual emissions in g-TEQ/yr. From this procedure, the emissions from all industrial boilers/furnaces burning hazardous waste as supplemental fuel are estimated as 0.38 g I-TEQ_{DF} (or 0.39 g TEQ_{DF}-WHO_{98}) in 1995 and 0.77 g I-TEQ_{DF} (or 0.78 g TEQ_{DF}-WHO_{98}) in 1987. Because of the low confidence rating for the emission factor, the overall confidence rating is low for both the 1987 and 1995 emission estimates.

3.2.7. Solid Waste from Hazardous Waste Combustion

U.S. EPA (1987a) contains limited data on ash generated from hazardous waste incineration. Table 3-8 of U.S. EPA (1987a) indicates that 538 μg/kg and 2,853 μg/kg were the mean concentrations of CDDs and CDFs, respectively, from a hazardous waste incinerator with an afterburner. Specific data for congeners and for ash quantities were not given.

3.3. MEDICAL WASTE INCINERATION

Medical waste incineration (MWI) is the controlled burning of solid wastes generated primarily by hospitals, veterinary, and medical research facilities. The U.S. EPA defines medical waste as any solid waste generated in the treatment, diagnosis, or immunization of humans or animals, or research pertaining thereto, or in the production or testing of biologicals (Federal Register, 1997b). The primary purposes of MWI are to reduce the volume and mass of waste in need of land disposal, and to sterilize the infectious materials. The following subsections review the basic types of MWI designs

used to incinerate medical waste, review the distribution of APCDs used on MWIs, summarize the derivation of dioxin TEQ emission factors for MWIs, and summarize the national dioxin TEQ emission estimates for reference years 1995 and 1987.

3.3.1. Design Types of MWIs Operating in the United States

For purposes of this document, EPA has classified MWIs into three broad technology categories: modular furnaces using controlled-air, modular furnaces using excess-air, and rotary kilns. Of the MWIs in use today, the vast majority are believed to be modular furnaces using controlled-air. EPA has estimated that 97 percent are modular furnaces using controlled-air, 2 percent are modular furnaces using excess air, and 1 percent are rotary kiln combustors (U.S. EPA, 1997b).

Modular Furnaces Using Controlled-air: Modular furnaces have two separate combustion chambers mounted in series (one on top of the other). The lower chamber is where the primary combustion of the medical waste occurs. Medical waste is ram-fed into the primary chamber, and underfire air is delivered beneath the incinerator hearth to sustain good burning of the waste. The primary combustion chamber is operated at below stoichiometric levels, hence the terms "controlled" or "starved-air." With sub-stoichiometric conditions, combustion occurs at relatively low temperatures (i.e., 760 to 985°C). Under the conditions of low oxygen and low temperatures, partial pyrolysis of the waste occurs, and volatile compounds are released. The combustion gases pass into a second chamber. Auxiliary fuel (such as natural gas) is burned to sustain elevated temperatures (i.e., 985 to 1,095°C) in this secondary chamber. The net effect of exposing the combustion gases to an elevated temperature is more complete destruction the organic contaminants entrained in the combustion gases emanating from the primary combustion chamber. Combustion air at 100 to 300 percent in excess of stoichiometric requirement is usually added to the secondary chamber. Gases exiting the secondary chamber are directed to an incinerator stack (U.S. EPA, 1997b; U.S. EPA, 1991d; Buonicore, 1992b). Figure 3-12 displays a schematic of a typical modular furnace using controlled-air. Because of it's low cost and good combustion performance, this design has been the most popular choice for MWIs and has accounted for more than 95 percent of systems installed over the past two decades (U.S. EPA, 1990d; U.S. EPA, 1991d; Buonicore, 1992b).

Modular Furnaces Using Excess-air: These systems use the same modular furnace configuration as described above for the controlled air systems. The difference is that the primary combustion chamber is operated at air levels of 100 percent to 300 percent in excess of stoichiometric requirements. Hence the name "excess-air." A secondary chamber is located on top of the primary unit. Auxiliary fuel is added to sustain high temperatures in an excess-air environment. Excess-air MWIs are typically smaller in capacity than controlled-air units and are usually batch-fed operations. This means that the medical waste is ram-fed into the unit and allowed to burn completely before another batch of medical waste is added to the primary combustion chamber.

Rotary Kiln MWI: This technology is similar in terms of design and operational features to the rotary kiln technology employed in both municipal and hazardous waste incineration. (See description in Section 3.1.) Because of their relatively high capital and operating costs, few rotary kiln incinerators are in operation for medical waste treatment (U.S. EPA, 1990d; U.S. EPA, 1991d; Buonicore, 1992b).

MWIs can be operated in three modes: batch, intermittent, and continuous. Batch incinerators burn a single load of waste, typically only once per day. Waste is loaded, and ashes are removed manually. Intermittent incinerators, loaded continuously and frequently with small waste batches, operate less than 24 hours per day, usually on a shift-type basis. Either manual or automated charging systems can be used, but the incinerator must be shut down for ash removal. Continuous incinerators are operated 24 hours per day and use automatic charging systems to charge waste into the unit in small, frequent batches. All continuous incinerators operate using a mechanism to automatically remove the ash from the incinerator (U.S. EPA, 1990d; U.S. EPA, 1991d).

3.3.2. Characterization of MWIs for Reference Years 1995 and 1987

MWI remains a poorly characterized industry in the United States in terms of knowing the exact number of facilities operational over time, the types of APCDs installed on these units, and the aggregate volume and weight of medical waste that is combusted in any given year (U.S. EPA, 1997b). The primary reason for this is that permits were not generally required for the control of pollutant stack emissions from MWIs until the early 1990s when State regulatory agencies began setting limits on emissions of particulate

matter and other contaminants (Federal Register, 1997b). Prior to that timeframe, only opacity was controlled.

The information available to characterize MWIs comes from national telephone surveys, stack emission permits, and data gathered by EPA during public hearings (Federal Register, 1997b). This information suggests the following:

- The number of MWIs in operation was approximately 5,000 in 1987 (U.S. EPA, 1987d) and 2,375 in 1995 (Federal Register, 1997b).
- The amount of medical waste combusted annually in the United States was approximately 1.43 billion kg in 1987 (U.S. EPA, 1987d) and 0.77 billion kg in 1995 (Federal Register, 1997b).

These estimates indicate that, between 1987 and 1995, the total number of operating MWIs and the total amount of waste combusted decreased by more than 50 percent. Certain activities caused this to occur, including more stringent air pollution control requirements by State regulatory agencies and the development of less expensive medical waste treatment technologies, such as autoclaving (Federal Register, 1997b). Because many MWIs have small waste charging capacity (i.e., about 50 metric tons per day), the installation of even elementary APCDs proved not to be cost effective. Thus, a large number of facilities elected to close rather than retrofit.

The actual controls used on MWIs on a facility-by-facility basis in 1987 are unknown, and EPA generally assumes that MWIs were mostly uncontrolled (U.S. EPA,1987d). However, the modular design does cause some destruction of organic pollutants within the secondary combustion chamber. Residence time within the secondary chamber is key to inducing the thermal destruction of the organic compounds. Residence time is the time that the organic compounds entrained within the flue gases are exposed to elevated temperatures in the secondary chamber. EPA has demonstrated with full-scale MWIs that increasing residence time from 1/4 second to 2 seconds in the secondary chamber can reduce organic pollutant emissions, including CDD/CDFs, by up to 90 percent (Federal Register, 1997b). In this regard, residence time can be viewed as a method of air pollution control.

EPA estimates that about two-thirds of medical waste burned in MWIs in 1995 went to facilities equipped with some method of air pollution control (Federal Register, 1997b). The types of APCDs installed and the methods used on MWIs include: dry

sorbent injection, fabric filters, electrostatic precipitators (ESPs), wet scrubbers, and fabric filters combined with packed-bed scrubbers (composed of granular activated carbon). Some organic constituents in the flue gases can be adsorbed by the packed bed. Within the uncontrolled class of MWIs, about 12 percent of the waste were combusted in facilities with design capacities of $<$200 lbs/hr, with the majority of waste burned facilities $>$200 lbs/hr. The estimated breakdown of controlled facilities is: 70 percent of the aggregate activity level are associated with facilities equipped with either wet scrubbers, fabric filters, or ESPs; 29.9 percent are associated with facilities utilizing dry sorbent injection, combined with fabric filters, and less than 1 percent is associated with facilities having the fabric filter/packed-bed APCD (AHA, 1995; Federal Register, 1997b).

3.3.3. Estimation of CDD/CDF Emissions from MWIs

Emission tests reported for 24 MWIs (i.e., about 1 percent of existing facilities) were collected for use in this report. Consequently, most facilities have unmeasured emission levels of dioxin-like compounds. Because so few have been evaluated, the estimation of annual air emissions of CDD/CDFs from MWIs is quite dependent on extrapolations, engineering judgement, and the use of assumptions. In addition, the information about the activity levels of these facilities is also quite limited. With these data limitations, two approaches have been used in the past to estimate CDD/CDF emissions from MWIs, and a third is proposed here. These three approaches are as follows:

1. **EPA/OAQPS Approach**: EPA's Office of Air Quality Planning and Standards (OAQPS) used this approach in support of the promulgation of final air emission standards for hospital/medical/infectious waste incinerators (Federal Register, 1997b).

2. **AHA Approach**: The American Hospital Association proposed an approach in its comments on drafts of this document and on the proposed MWI emissions regulations (AHA, 1995).

3. **EPA/ORD Approach**: In preparation of this document, EPA's Office of Research and Development (ORD) has developed a third approach.

Given the limitations with existing information, both the EPA/OAQPS and AHA approaches are reasonable methods for calculating annual releases of CDD/CDFs from MWIs. Both

methods relied heavily on a series of assumptions to account for missing information. In developing a third approach, EPA/ORD built upon the other two approaches by utilizing the most logical features of each. Because of the uncertainties with existing data, it is currently not known which approach gives the most accurate estimate of CDD/CDF air emissions from all MWIs, nationwide. The three approaches yield different air emission estimates, but the estimates all agree within a factor of four. As discussed below, the EPA/ORD approach used the strengths of the other two approaches, and represents some improvement in estimating CDD/CDF emissions.

3.3.4. EPA/OAQPS Approach for Estimating CDD/CDF Emissions from MWIs

On September 15, 1997, EPA promulgated final standards of performance for new and existing MWIs under the Clean Air Act Amendments (Federal Register, 1997b). CDD/CDF stack emission limits for existing MWIs were established as follows: 125 ng/dscm of total CDD/CDF (at 7 percent O_2, 1 atm), equivalent to 2.3 ng/dscm TEQ. In order to evaluate emissions reductions that will be achieved by the standard, OAQPS estimated, as a baseline for comparison, nationwide annual CDD/CDF emissions from all MWIs operating in 1995.

3.3.4.1. *EPA/OAQPS Approach for Estimating Activity Level*

As a starting point for deriving the national estimates, OAQPS constructed an inventory of the numbers and types of MWIs believed to be operating in 1995. The inventory was based on an inventory of 2,233 MWIs prepared by the American Hospital Association (AHA, 1995), supplemented with additional information compiled by EPA. This created a listing of 2,375 MWIs in the United States. Next a series of assumptions were used to derive activity level estimates, as follows:

1. The analysis divided MWIs into three design types based on the mode of daily operation: batch, intermittent, and continuous. This was done using the information from the inventory on design-rated annual incineration capacity of each facility. The smaller capacity units were assumed to be batch operations, and the others were classified as either intermittent or continuous, assuming a ratio of three to one.

2. The activity level of each facility was estimated by multiplying the design-rated annual incineration capacity of the MWI (kg/hr) by the hours of

operation (hr/yr). The annual hours of operation were determined by assuming a capacity factor (defined as the fraction of time that a unit operates over the year) for each design type of MWI (Randall, 1995). Table 3-9 is a summary of the OAQPS estimated annual operating hours per MWI design type.

3.3.4.2. *EPA/OAQPS Approach for Estimating CDD/CDF Emission Factors*

Based on information obtained from AHA and State regulatory agencies, one-third of the population of MWIs operating in 1995 was etimated to have had no APCDs (i.e., were uncontrolled), and two-thirds had some type of APCD. CDD/CDF TEQ emission factors were then developed for uncontrolled and controlled MWIs. The procedure was as follows:

Estimating TEQ Emission Factors for Uncontrolled Facilities: The uncontrolled category of facilities was subdivided by residence time of the secondary combustion chamber. Based on tests at three MWIs, OAQPS concluded that stack emissions of CDD/CDFs from uncontrolled facilities were dependent on the residence time (i.e., the duration of time the compounds are exposed to elevated temperatures within the secondary combustion chamber) (Strong, 1996). The tests demonstrated that when the residence time in the secondary chamber was short (i.e., <1 sec), the stack emissions of CDDC/CDFs would increase; conversely, the longer the residence time (i.e., >1 sec), the CDD/CDF emissions decrease. The emissions testing at these MWIs provided the basis for the derivation of I-TEQ_{DF} emission factors for residence times of 1/4-sec, 1-sec and 2-sec. Table 3-10 is a summary of the emission factors developed for each MWI type as a function of residence time.

The OAQPS inventory of MWIs in 1995 did not provide residence times for each facility. OAQPS overcame this data gap by assuming that residence time in the secondary combustion chamber approximately corresponds with the particulate matter (PM) stack emission limits established in State air permits. This approach assumed that the more stringent PM emission limits would require longer residence times in the secondary chamber in order to further oxidize carbonaceous soot particles and reduce PM emissions. Table 3-10 lists the assumed residence times in the secondary chamber corresponding to various State PM emission limits. State Implementation Plans (SIPs) were reviewed to determine the PM emission limits for incinerators, and from this review, both a residence

time and an I-TEQ_{DF} emission factor were assigned to each uncontrolled MWI on the inventory.

Estimating TEQ Emission Factors for Controlled MWIs: Two-thirds of the MWI population were assumed to have some form of APCD. As previously discussed, APCDs typically used by MWIs consist of one or more of the following: wet scrubber, dry scrubber, and fabric filter combined with a packed bed. The EPA/OAQPS approach also included the addition of activated carbon to the flue gases as a means of emissions control (i.e., dry scrubbers combined with carbon injection). TEQ emission factors were developed for these control systems based on incinerator emissions testing data gathered in support of the regulations (U.S. EPA, 1997b). Because the inventory did not list the APCDs for all MWIs, State requirements for PM control were used to make assumptions about the type of APCD installed on each facility in the inventory. These assumptions are summarized in Table 3-11.

3.3.4.3. *EPA/OAQPS Approach for Estimating Nationwide CDD/CDF TEQ Air Emissions*

Annual TEQ emissions for each MWI facility were calculated as a function of the design capacity of the incinerator, the annual waste charging hours, the capacity factor, and the TEQ emission factor as shown in Equation 3-6.

$$E_{mwi} = (C \times H \times C_1) \times F_{TEQ} \qquad \text{(Eqn. 3-6)}$$

Where:

E_{mwi}	=	Annual MWI CDD/F TEQ stack emissions (g/yr)
C	=	MWI design capacity (kg/hr)
H	=	Annual medical waste charging hours (hr/yr)
C_1	=	Capacity factor (unitless)
F_{TEQ}	=	CDD/CDF TEQ emission factor (g TEQ/kg)

The annual TEQ air emission of all MWIs operating in 1995 is the sum of the annual emissions of each individual MWI. The following equation is applied to estimate annual TEQ emissions from all MWIs.

$$E_{mwi}(\text{nationwide}) = (Em_{mwi_1} + Em_{mwi_2} + + \ldots\ldots + Em_{mwi_{2375}}) \qquad \text{(Eqn. 3-7)}$$

Where:

E_{mwi}(nationwide) = Nationwide MWI TEQ emissions (g/yr)

Table 3-11 is a summary of I-TEQ_{DF} emissions for 1995 estimated using the EPA/OAQPS Approach.

3.3.5. AHA Approach for Estimating CDD/CDF Emissions from MWIs

In 1995, the American Hospital Association (AHA) submitted written comments to EPA in response to EPA's request for public comment of the 1994 draft public release of this document (AHA, 1995). As part of these comments, the AHA attached an analysis of CDD/CDF emissions from MWIs prepared by Doucet (1995) for the AHA. Doucet (1995) estimated the total number of MWIs operating in 1995, the distribution of APCDs, CDD/CDF TEQ emission factors, and the nationwide TEQ emissions. The following is a brief discussion of the AHA inventory and the Doucet (1995) analysis.

From a national telephone survey of member hospitals conducted between September and November 1994, the AHA developed what is generally considered as the first attempt to systematically inventory MWIs in the United States. Approximately 6 percent of the hospitals with MWIs were contacted (AHA,1997). The AHA survey showed that, as of December 1994, 2,233 facilities were in operation. Doucet (1995) subdivided the AHA MWI inventory into two uncontrolled categories based on combustor design-rated capacity and two controlled categories based on APCD equipment. Doucet (1995) then developed CDD/CDF emission factors for each MWI category. Test reports of 19 MWIs were collected and evaluated. Average CDD/CDF TEQ flue gas concentrations (i.e., ng/dscm @7 percent O_2) were derived by combining tests from several MWIs in each capacity range category and APCD. The average TEQ flue gas concentrations were then converted to average TEQ emission factors, which were in units of lb TEQ/10^6 lbs of medical waste incinerated (equation for conversion not given). Table 3-12 lists the I-TEQ_{DF} emission factors calculated by Doucet (1995) for each level of assumed APCDs on MWIs.

Similar to the EPA/OAQPS Approach (Section 3.3.4), the distribution of the APCD categories was derived by assuming that State particulate emission (PM) limits would indicate the APCD on any individual MWI (Doucet, 1995). Table 3-13 displays the AHA assumptions of air pollution control (APC) utilized on MWIs based upon PM emission limits.

With the activity levels, the percent distribution of levels of controls, and the CDD/CDF TEQ emission factors having been calculated with existing data, the final step of the AHA Approach was the estimation of annual I-TEQ_{DF} emissions (g/yr) from MWIs, nationwide. Although no equation is given, it is presumed that the emissions were estimated by multiplying the activity level for each MWI size and APCD category by the associated I-TEQ_{DF} emission factor. The sum of these calculations for each designated class yields the estimated annual I-TEQ_{DF} emissions for all MWIs, nationwide. Doucet (1995) indicates that these computations are appropriate for I-TEQ_{DF} emissions in 1995. Table 3-14 summarizes the nationwide annual I-TEQ_{DF} emissions from MWIs using the AHA Approach.

3.3.6. EPA/ORD Approach for Estimating CDD/CDF Emissions from MWIs

Because of limitations in emissions data and on activity levels, the EPA/ORD approach used many of the logical assumptions developed in the EPA/OAQPS and AHA approaches. The discussion below describes the rationale for how these decisions were made, and presents the resulting emission estimates.

3.3.6.1. *EPA/ORD Approach for Classifying MWIs and Estimating Activity Levels*

As with the EPA/OAQPS and AHA approaches, the EPA/ORD approach divided the MWIs into controlled and uncontrolled classes. The decisions about further dividing these two classes are described below:

Uncontrolled MWIs: For purposes of assigning CDD/CDF emission factors and activity levels to the uncontrolled class of MWIs, the EPA/OAQPS approach divided this class on the basis of residence time within the secondary combustion chamber. This approach has theoretical appeal, because it is logical to expect more complete combustion of CDD/CDFs with longer residence times at high temperatures. Unfortunately, the residence times on a facility-by-facility basis are not known, making it difficult to assign

emission factors and activity levels on this basis. As discussed earlier, the EPA/OAQPS approach assumed that residence time would strongly correlate with State PM stack emission requirements (i.e., the more stringent the PM requirements, the longer the residence time required to meet the standard). This PM method for estimating residence time resulted in the following distribution of residence times: 6 percent of the waste incinerated at MWIs with 1/4-sec residence time; 26 percent of the waste incinerated at MWIs with 1-sec residence time; and 68 percent of the waste incinerated at MWIs with 2-sec residence time. Thus, about two-thirds of the activity level within the uncontrolled class were assumed in the EPA/OAQPS approach to be associated with facilities with the longest residence time and the lowest CDD/CDF emission factor.

The AHA approach subcategorized the uncontrolled class on the basis of design-rated capacity. There is also theoretical support for this approach. Smaller capacity operations (i.e., $<$200 lb/hr) are likely to have higher emissions, because they are more likely to be operating in a batch mode. The batch mode results in infrequent operation with more start-up and shut-down cycles. Thus, the batch-operated MWI usually spends more time outside of the ideal range of operating conditions. In support of this approach, the AHA presented limited empirical evidence indicating that CDD/CDF emission factors calculated from emission test reports for the low capacity units were about a factor of two higher than the emission factors for the high capacity units (Doucet, 1995).

Thus, both the EPA/OAQPS and AHA approaches have a sound theoretical basis but lack strong supporting data. In order to decide which of the two approaches to use, ORD first tested the assumption that there is a strong relationship between State PM requirements and residence time. ORD conducted a limited telephone survey of regulatory agencies in four States where a large number of MWI facilities were in operation: Michigan, Massachusetts, New Jersey, and Virginia (O'Rourke, 1996). The results of the limited survey, summarized in Table 3-15, did not verify the existence of a strong dependent relationship between PM emission limits and residence time in the secondary chamber at MWIs.

Next, the available emission testing data for small and high capacity units (i.e., less than and greater than 200 lb/hr) were evaluated to determine if, as posited in the AHA approach, smaller capacity units have greater emission factors than large capacity units. This evaluation indicated a distinct difference in the emission factors between the two

capacity categories, although the difference in the set of data evaluated was not as great as the difference observed in the data set evaluated in the AHA approach. The EPA/ORD approach, therefore, adopted the subcategorization scheme used in the AHA approach.

Controlled MWIs: Both the EPA/OAQPS approach and the AHA approach subcategorized the controlled MWIs on the basis of APCD equipment. However, the two approaches differed in the subcategories developed. The AHA approach divided the controlled class into two groups: facilities equipped with wet scrubbers (alone, with an ESP, or with a fabric filter), and facilities equipped with dry sorbent injector and a fabric filter (Doucet, 1995). The EPA/OAQPS approach divided the controlled class into three groups: facilities equipped with wet scrubbers, facilities equipped with dry scrubbers (with or without carbon injection), and facilities equipped with fabric filters and packed bed scrubbers. This third category is comprised of a few facilities primarily located in the Northeast United States (O'Rourke, 1996). The EPA/ORD approach adopted the two subcategories of the AHA approach and the third subcategory of the EPA/OAQPS approach. For 1995, EPA/ORD used the activity levels for each facility as reported in the EPA/OAQPS inventory; the activity levels were then summed across facilities for each APCD subclass.

For 1987, the EPA/ORD approach assumed that every MWI was uncontrolled. An EPA study of MWI incineration conducted at that time indicates that MWIs operating in 1987 did not need controls, because they were not subject to State or Federal limits on either PM or organic pollutant emissions (U.S. EPA, 1987d). The activity level estimates were derived from data presented in U.S. EPA (1987d). This approach resulted in the following activity level assumptions for 1987: (a) 15 percent of the activity level (i.e., 0.22 billion kg medical waste) were incinerated/yr by MWIs with capacities less than or equal to 200 lb/hr, and (b) 85 percent of the activity level (i.e., 1.21 billion kg/yr) were incinerated by facilities with capacities greater than 200 lb/hr.

3.3.6.2. *EPA/ORD Approach for Estimating CDD/CDF Emission Factors*

EPA/ORD collected the engineering reports of 24 tested MWIs. After reviewing these test reports, 20 met the criteria for acceptability. (See Section 3.1.3 for further details on the criteria.) In some cases, CDD/CDF congener-specific data were not reported, or values were missing. In other cases, the protocols used in the laboratory

analysis were not described; therefore, no determination of the adequacy of the laboratory methods could be made.

The EPA stack testing method (EPA Method 23) produces a measurement of CDD/CDFs in units of mass concentration (i.e., nanograms per dry standard cubic meter of combustion gas (ng/dscm)) at standard temperature and pressure and one atmosphere and adjusted to a measurement of 7 percent oxygen in the flue gas (U.S. EPA, 1995b). This concentration is assumed to represent conditions at the point of release from the stack into the air, and to be representative of routine emissions. The emission factors were derived by averaging the emission factors across each tested facility in a design class. The emission factor for each tested MWIs was calculated using the following equation:

$$EF_{mwi} = \frac{C \times F_v}{I_w} \qquad \text{(Eqn. 3-8)}$$

Where:

EF_{mwi} = Emission Factor per MWI (average ng TEQ per kg of medical waste burned)

C = Average TEQ concentration in flue gases of tested MWIs (ng TEQ/dscm) (20°C, 1 atm; adjusted to 7% O_2)

F_v = Average volumetric flue gas flow rate (dscm/hr) (20°C, 1 atm; adjusted to 7% O_2)

I_w = Average medical waste incineration rate of the tested MWI (kg/hr)

The emission factor estimate for each design class and the number of stack tests used to derive it are shown in Table 3-16. Figures 3-12 and 3-13 present congener and congener group profiles for air emissions from MWIs lacking APCDs and for MWIs equipped with a wet scrubber/baghouse/fabric filter APCD system, respectively.

3.3.7. Summary of CDD/CDF Emissions from MWIs

Because the stack emissions from so few facilities have been tested (i.e., 20 test reports) relative to the number of facilities in this industry (i.e., 2,375 facilities in 1995 and 5,000 facilities in 1987) and because several tested facilities are no longer in operation or have installed new APCD after testing, the EPA/ORD approach did not calculate nationwide CDD/CDF emissions by calculating emissions from the tested

facilities and adding those to calculated emissions for the non-tested facilities. Rather, the EPA/ORD approach (as well as the EPA/OAQPS and AHA approaches) calculated nationwide CDD/CDF emissions by multiplying the emission factor and activity level developed for each design class and then summing the calculated emissions for all classes. Tables 3-16 and 3-17 summarize the resulting national TEQ air emissions for the reference years 1995 and 1987, respectively. Tables 3-16 and 3-17 also indicate the activity level and the TEQ emission factor used in estimating annual TEQ emissions.

In estimating annual TEQ emissions in both reference years, a low confidence rating was assigned to the estimate of the activity level. The primary reason for the low confidence rating is that very limited information is available on a facility level basis for characterizing MWIs in terms of the frequency and duration of operation, the actual waste volume handled, and the level of pollution control. The 1987 inventory of facilities was based on very limited information. Although the 1995 EPA/OAQPS inventory was more comprehensive than the 1987 inventory, it was still based on a fairly limited survey of operating facilities (i.e., approximately 6 percent).

The emission factor estimates were given a low confidence rating, because only the reports of 20 tested MWI facilities could be used to derive emissions factors representing the 2,375 facilities operating in 1995 (i.e., less than 1 percent of estimated number of operating facilities). Even fewer tested facilities could be used to represent the larger number of facilities operating in 1987 (i.e., 8 tested facilities were used to represent 5,000 facilities). The limited emission tests available do cover all design categories used here to develop emission factors. However, because of the large number of facilities in each of these classes, it is very uncertain whether the few tested facilities in each class capture the true variability in emissions. As shown in Table 3-16, the TEQ emissions in 1995 are estimated to have been 461 g I-TEQ_{DF} or 488 g TEQ_{DF}-WHO_{98}. As shown in Table 3-17, the TEQ emissions in 1987 are estimated to have been 2,440 g I-TEQ_{DF} or 2,590 g TEQ_{DF}-WHO_{98}.

As explained above, the EPA/ORD approach to estimating national CDD/CDF TEQ emissions is a 'hybridization' of the EPA/OAQPS and AHA approaches. Table 3-18 compares the main features of each of the three approaches. The 1995 TEQ emissions estimated here (461 g I-TEQ_{DF}/yr) are about 3.5 times higher than those of OAQPS and AHA (141 and 138 g I-TEQ_{DF}/yr, respectively). Most of this difference is due to

differences in the emission estimates for the uncontrolled facilities (ORD - 432 g I-TEQ_{DF}/yr, OAQPS - 136 g I-TEQ_{DF}/yr, AHA - 120 g I-TEQ_{DF}/yr). An analysis of the differences in how these groups estimated emissions from the uncontrolled facilities are presented below:

- **Differences between the EPA/ORD and AHA Approaches:** The ORD approach adopted the classification scheme of the AHA approach for the uncontrolled class and assumed similar activity levels. Thus, the difference in emission estimates is primarily due to differences in the emission factors used. Both groups use similar emission factors for facilities with design capacities less than or equal to 200 lbs/h, but the emission factor for MWIs >200 lbs/hr used in the EPA/ORD approach was higher than that used in the AHA approach by a factor of three. This results from the fact that the two approaches used different sets of emission tests to derive their emission factors.

- **Differences between the EPA/ORD and EPA/OAQPS Approaches**: Because the two approaches subcategorized the uncontrolled facilities into different classes, the activity levels and emission factors cannot be directly compared. Considering the class as a whole, however, both approaches used essentially identical activity levels. The EPA/OAQPS approach assigned 68 percent of the total activity to the class with the lowest emission factor (i.e., those with >2-sec residence time). The emission factor for this class, 74 ng I-TEQ_{DF}/kg, is considerably lower than either emission factor used in the EPA/ORD approach (1,680 and 1,860 ng I-TEQ_{DF}/kg).

Given the uncertain data base available for making these estimates, it is difficult to know which of these three estimation approaches yields the most accurate annual TEQ estimate. However, despite the differences in methodologies and assumptions used, the three approaches yield annual TEQ estimates that are not fundamentally different; the estimates differ from each other by a factor of four or less. Because the EPA/ORD approach was the last of the three to be developed, it has the benefit of being able to utilize the most logical and supportable features of the previously developed EPA/OAQPS and AHA approaches.

3.3.8. Recent EPA Regulatory Activities

Regardless of the approach taken to estimate what the CDD/CDF emissions from 2,375 MWIs were in 1995, the National Emission Standards promulgated by EPA in September 1997 (Federal Register, 1997b) require substantial reductions of CDD/CDF air emissions from MWIs. As a result of these standards, MWI emissions will be thoroughly assessed for purposes of compliance with the CDD/CDF standard. Compliance testing will allow the development of a more comprehensive emissions data base and more accurate characterization of this industry. EPA projects that, following full compliance with these standards, annual emissions will be 5 to 7g I-TEQ_{DF}year.

3.4. CREMATORIA

Bremmer et al. (1994) measured CDD/CDF emissions at two crematoria in The Netherlands. The first, a "cold" type furnace with direct uncooled emissions, was calculated to yield 2.4 μg I-TEQ_{DF} per body. In the cold type furnaces, the coffin is placed inside at a temperature of about 300°C. Using a burner, the temperature of the chamber is increased to 800 to 900°C and kept at that temperature for 2 to 2.5 hours. The second furnace, a "warm" type with cooling of flue gases to 220°C prior to discharge, was calculated to yield 4.9 μg I-TEQ_{DF} per body. In the warm type furnace, the coffin is placed in a chamber preheated to 800°C or higher for 1.2 to 1.5 hours. The chamber exhausts from both furnace types were incinerated in an after burner at a temperature of about 850°C. The higher emission rate for the warm-type furnace was attributed by Bremmer et al. (1994) to the formation of CDD/CDF during the intentional cooling of the flue gases to 220°C.

Jager et al. (1992) (as reported in Bremmer et al., 1994) measured an emission rate of 28 μg I-TEQ_{DF} per body for a crematorium in Berlin, Germany. No operating process information was provided by Bremmer et al. (1994) for the facility.

Mitchell and Loader (1993) reported even higher emission factors for two crematoria in the United Kingdom. The first facility tested was manually-operated, had primary and secondary combustion chambers preheated to 650°C, and had a residence time of 1 second in the secondary combustion chambers. The second tested facility was computer-controlled, had primary and secondary combustion chambers heated to 850°C, and had a residence time of 2 seconds in the secondary combustion chamber. The

measured stack gas concentrations of I-TEQ_{DF} ranged from 42.0 to 71.3 ng I-TEQ_{DF}/m^3 (at 11% O_2) at the first facility and from 25.4 to 45.5 ng I-TEQ_{DF}/m^3 (at 11% O_2) at the second facility. Emission factors based on these test results and gas generation rates reported by Bremmer et al. (1994) were calculated to range from 70 to 80 μg I-TEQ_{DF}/body (HMIP, 1995).

Takeda et al. (1998) measured CDD/CDF emissions at 10 crematoria in Japan. Although there are more than 1,600 crematoria in Japan, the 10 tested facilities handle four percent of the cremations carried out in Japan annually. A wide range in emission factors was observed. When not-detected values are treated as zero, the range was 0.042 to 62 μg I-TEQ_{DF}/body (mean of 9.2 μg I-TEQ_{DF}/body). When not-detected values are treated as one-half the detection limit, the range was 0.45 to 63 μg I-TEQ_{DF}/body (mean of 11 μg I-TEQ_{DF}/body).

In the United States, CDD/CDF emissions have been measured at one crematorium (CARB, 1990c) classified as a warm type facility using the criteria of Bremmer et al. (1994). The combusted material at this facility was comprised of the body, as well as 4 pounds of cardboard, up to 6 pounds of wood, and an unquantified amount of unspecified plastic wrapping. The three emission tests conducted at this facility yielded an average emission factor of 0.50 μg I-TEQ_{DF}/body (or 0.54 μg TEQ_{DF}-WHO_{98}/body). Table 3-19 presents the congener-specific emission factors for this facility. Figure 3-14 presents CDD/CDF congener and congener group emission profiles based on these emission factors.

The emission factor measured at the one tested U.S. facility is at the lower end of the range reported for 10 Japanese facilities by Takeda et al. (1998) and is also lower than the results reported by Bremmer et al. (1994) for two Dutch facilities, by Jager et al. (1992) for one German facility, and by Mitchell and Loader (1993) for two British facilities. The average emission factor for these 16 tested facilities is 17 μg I-TEQ_{DF}/body (assuming not-detected values are zero). Because congener-specific results were not provided in the non-U.S. reports, it was not possible to calculate the average emission factor in units of TEQ_{DF}-WHO_{98}. This average emission factor is assigned a low confidence rating because it is based primarily on tests conducted at non-U.S. facilities.

In 1995, there were 1,155 crematories reported in the United States. However, there are no readily available data on the number of cold versus warm crematoria furnaces. In 1995, 21.1 percent of the deceased bodies were cremated (i.e., 488,224

cremations), and 15.2 percent of the deceased were cremated in 1987 (i.e., 323,371 cremations). Cremations are projected to increase to 25 percent in the year 2000 and 37 percent in the year 2010. A high confidence rating is assigned to these activity level estimates, because they are based on recent data provided by the Crematoria Association of North America (Springer, 1997).

Combining this average emission rate of 17 μg I-TEQ$_{DF}$/body with the number of cremations in 1995 (488,224) yields an estimated annual release of 9.1 g I-TEQ$_{DF}$. Combining the emission rate of 17 μg I-TEQ$_{DF}$/body with the number of cremations in 1987 (323,371) yields an estimated release of 5.5 g.

3.5. SEWAGE SLUDGE INCINERATION

The three principal combustion technologies used to incinerate sewage sludge in the United States are the multiple-hearth incinerator, fluidized-bed incinerator, and the electric furnace (Brunner, 1992; U.S. EPA, 1995b). All of these technologies are "excess-air" processes (i.e., they combust sewage sludge with oxygen in excess of theoretical requirements). Approximately 80 percent of operating sludge incinerators are multiple-hearth design. About 20 percent are fluidized-bed incinerators, and less than 1 percent are electric incinerators. Other types of technologies not widely used in the United States are single-hearth cyclones, rotary kilns, and high-pressure wet-air oxidation (U.S. EPA, 1997b; Maw, 1998).

Multiple-hearth Incinerator: This consists of refractory hearths arranged vertically in series, one on top of the other. Dried sludge cake is fed to the top hearth of the furnace. The sludge is mechanically moved from one hearth to another through the length of the furnace. Moisture is evaporated from the sludge cake in the upper hearths of the furnace. The center hearths are the burning zone, where gas temperatures reach 871°C. The bottom hearths are the burn-out zone, where the sludge solids become ash. A waste-heat boiler is usually included in the burning zone, where steam is produced to provide supplemental energy at the sewage treatment plant. Air pollution control measures typically include a venturi scrubber, an impingement tray scrubber, or a combination of both. Wet cyclones and dry cyclones are also used (U.S. EPA, 1995b).

Fluidized-bed Incinerator: This is a cylindrical refractory-lined shell with a steel plate structure that supports a sand bed near the bottom of the furnace (Brunner, 1992).

Air is introduced through openings in the bed plate supporting the sand. This causes the sand bed to undulate in a turbulent air flow; hence, the sand appears to have a fluid motion when observed through furnace portals. Sludge cake is added to the furnace at a position just above this fluid motion of the sand bed. The fluid motion promotes mixing in the combustion zone. Sludge ash exits the furnace with the combustion gases; therefore, air pollution control systems typically consist of high-energy venturi scrubbers. Air pollution control measures typically include a venturi scrubber or venturi/impingement tray combinations (U.S. EPA, 1995b).

Electric Furnaces: Also called infrared furnaces, these consist of a long rectangular refractory-lined chamber. A belt conveyer system moves the sludge cake through the length of the furnace. To promote combustion of the sludge, supplemental heat is added by electric infrared heating elements within the furnace that are located just above the traveling belt. Electric power is required to initiate and sustain combustion. Emissions are usually controlled with a venturi scrubber or some other wet scrubber (Brunner, 1992; U.S. EPA, 1995b).

3.5.1. Emission Estimates from Sewage Sludge Incinerators

EPA measured CDD/CDF emissions at three multiple-hearth incinerators as part of Tier 4 of the National Dioxin Survey (U.S. EPA, 1987a). During the pre-test surveys, two of the facilities were judged to have "average" potential and one facility was judged to have "high" potential for CDD/CDF emissions with respect to other sewage sludge incinerators. The results of these tests include congener group concentrations in stack gas, but lack measurement results for specific congeners other than 2,3,7,8-TCDD and 2,3,7,8-TCDF. EPA measured CDD/CDF emissions (including all 17 toxic congeners) at a fluidized-bed incinerator and a multiple hearth incinerator in 1990 (U.S. EPA, 1990f). In 1995, the Association of Metropolitan Sewerage Agencies (AMSA) submitted to EPA the results of stack tests conducted at an additional 13 sewage sludge incinerators (Green et al., 1995). Two of these data sets were considered not useable by EPA, because either detection limits or feed rates and stack flow rates were not provided. The average congener and congener group emission factors are presented in Table 3-20 for the three facilities from U.S. EPA (1987a) and the 11 AMSA facilities from Green et al. (1995). A wide variability was observed in the emission factors for the tested facilities. The total

CDD/CDF emission factors for the three U.S. EPA (1987a) facilities ranged from 90 to 3,400 ng/kg. The total CDD/CDF emission factors for the two facilities reported in U.S. EPA (1990f) were 79 to 846 ng/kg. For the 11 facilities reported in Green et al. (1995), a similarly large variability in emission factors was observed. Figure 3-15 presents the average congener and congener group profiles based on these data.

The average TEQ emission factor based on the data for the 11 AMSA facilities and the two facilities reported in U.S. EPA (1990f) is 6.94 ng I-TEQ_{DF}/kg of dry sludge combusted (or 7.04 ng TEQ_{DF}-WHO_{98}/kg of dry sludge), assuming nondetected values are zero. Other countries have reported similar results. Bremmer et al. (1994) reported an emission rate of 5 ng I-TEQ_{DF}/kg for a fluidized-bed sewage sludge incinerator, equipped with a cyclone and wet scrubber, in The Netherlands. Cains and Dyke (1994) measured CDD/CDF emissions at two sewage sludge incinerators in the United Kingdom. The emission rate at an incinerator equipped with an electrostatic precipitator and wet scrubber ranged from 2.75 ng I-TEQ_{DF}/kg to 28.0 ng I-TEQ_{DF}/kg. The emission rate measured at a facility equipped with only an electrostatic precipitator was 43.0 ng I-TEQ_{DF}/kg.

In 1988, approximately 199 sewage sludge incineration facilities combusted about 0.865 million metric tons of dry sewage sludge (Federal Register, 1993b). In 1995, approximately 257 sewage sludge incinerators (some of which were backup or alternate incinerators) combusted about 2.11 million dry metric tons of sewage sludge (Maw, 1998). Given these estimated amounts of sewage sludge incinerated/yr, the estimate of TEQ emissions to air is 6.0 g I-TEQ_{DF} (or 6.1 g TEQ_{DF}-WHO_{98}) in 1987 and 14.6 g I-TEQ_{DF} (or 14.8 g TEQ_{DF}-WHO_{98}) in 1995, using the average TEQ emission factor of 6.94 ng I-TEQ_{DF}/kg (7.04 ng TEQ_{DF}-WHO_{98}/kg).

A medium confidence rating is assigned to the average TEQ emission factor because it was derived from stack testing at 13 U.S. sewage sludge incinerators. The 1988 activity level estimate (used as a surrogate for the 1987 activity level) is assigned a high confidence rating, because it is based on an extensive EPA survey to support rulemaking activities. The 1995 activity level estimate is assigned a medium confidence rating because assumptions concerning hours of operation, operating capacity, and design capacity were made for numerous facilities.

3.5.2. Solid Waste from Sewage Sludge Incinerators

In Table 5-16 of U.S. EPA (1987a), data are presented indicating that 2,3,7,8-TCDD was not detected in the bottom ash or scrubber water filtrate from three sewage sludge incinerators. However, total CDDs for the three incinerators and the filtrate were: non-detect, 20 ng/kg, 10 ng/kg, and 0.3 ng/kg, respectively. For total CDFs, the respective values were: non-detect, 70 ngk/kg, 50 ng/kg, and 4.0 ng/kg. No data were given for any congeners (other than 2,3,7,8-TCDD), nor were there any data on the quantities of ash or filtrate.

3.6. TIRE COMBUSTION

Emissions of CDD/CDFs from the incineration of automobile tires were measured from a dedicated tire incinerator tested by the California Air Resources Board (CARB, 1991a). The facility consists of two excess air furnaces equipped with steam boilers to recovery the energy from the heat of combustion. Discarded whole tires were fed to the incineration units at rates ranging from 2,800 to 5,700 kg/hr during the 3 test days. The facility was equipped with a dry acid gas scrubber and fabric filter for the control of emissions prior to exiting the stack. Table 3-21 presents the congener-specific emission factors for this facility. Figure 3-16 presents CDD/CDF congener and congener group profiles based on these TEQ emission factors. From these data, the average emission factor is estimated to be 0.282 ng I-TEQ_{DF}/kg of tires incinerated (or 0.281 ng TEQ_{DF}-WHO_{98}) when all not detected values are treated as zero.

Cains and Dyke (1994) reported much higher emission rates for two tire incinerators equipped only with simple grit arrestors in the United Kingdom, 188 and 228 ng I-TEQ_{DF}/kg of combusted tire.

EPA estimated that approximately 0.50-million metric tons of tires were incinerated in 1990 in the United States (U.S. EPA, 1992a). This activity level estimate is given a medium confidence rating, because it is based on both published data and professional judgement. The use of scrap tires as a fuel was reported to have increased significantly during the late 1980s; however, no quantitative estimates were provided in U.S. EPA (1992a) for this period. In 1990, 10.7 percent of the 242 million scrap tires generated were burned for fuel. This percentage is expected to continue to increase (U.S. EPA, 1992a). Of the tires burned for energy recovery purposes, approximately 46 percent were

utilized by pulp and paper facilities, 23 percent were utilized by cement kilns, and 19 percent were utilized by one tire-to-energy facility (U.S. EPA, 1995c). Estimates of CDD/CDF emissions from cement kilns (inclusive of emissions from combustion of tires) are addressed in Section 5.1 of this report.

If it is assumed that 385 million kilograms of discarded tires were incinerated in the United States in 1987 and 1995 by facilities other than cement kilns (i.e., 500 million kg less approximately 115 million kg burned by cement kilns), then, using the TEQ emission factor derived from stack data from the one tested facility, an average of 0.11 grams of I-TEQ_{DF} (or 0.11 g TEQ_{DF}-WHO_{98}) per year are estimated to have been emitted to the air in both of these reference years. It must be noted that this may be an underestimate of emissions from this source category, because the one facility tested is a dedicated tire combustion facility and is equipped with a dry scrubber combined with a fabric filter for air pollution control. These devices are capable of greater than 95 percent reduction and control of dioxin-like compounds prior to discharge from the stack. It is not known to what extent other facilities combusting tires are similarly controlled. If such facilities are not so equipped, then the emission of CDD/CDF TEQ could be much greater than the estimates developed above. Therefore, the estimated emission factor for tire incineration is given a low confidence rating.

3.7. COMBUSTION OF WASTEWATER SLUDGE AT BLEACHED CHEMICAL PULP MILLS

Approximately 20.5 percent of the wastewater sludges generated at bleached chemical pulp mills are dewatered and burned in bark boilers at the pulp mills. These sludges can contain CDD/CDFs and elevated levels of chloride. However, the level of heat input from sludge in the mixed feed to bark boilers rarely exceeds 10 percent (NCASI, 1995).

NCASI (1995) provided congener-specific test results for four wood residue/sludge boilers tested between 1987 to 1993. Sludge comprised 6 to 10 percent of the solids in the feed. The average congener-specific emission factors derived from the stack test results obtained from these facilities are presented in Table 3-22. The average TEQ emission factors derived from the test results are 0.061 ng I-TEQ_{DF}/kg of feed (i.e., sludge and wood residue) (or 0.062 ng I-TEQ_{DF}-WHO_{98}), assuming nondetected values are zero. The range in facility-specific emission factors was wide (0.0004 to 0.118 ng I-TEQ_{DF}/kg

assuming nondetected values are zero). NCASI (1995) also presented stack emission test results for five other bark boilers. These boilers combusted only bark during the tests even though the boilers normally fire bark in combination with sludge and coal. These are discussed in Section 4.2.2 for industrial facilities burning wood scrap/residues. The average TEQ emission factor for these facilities was 0.4 ng I-TEQ_{DF}/kg of feed. The emissions test data presented in NCASI (1995), and discussed above, indicate that the CDD/CDF emission factors for bark/sludge combustors are similar to the emission factor developed in Section 4.2.2 for industrial facilities burning only wood residues/scrap. Based on the fact that wood residues comprise a far greater fraction of the feed to these bark/sludge burners than does sludge, the national TEQ emission estimates derived in Section 4.2.2 of this report for industrial wood burning facilities are assumed to include emissions from these bark/sludge combustion units.

3.8. BIOGAS COMBUSTION

Using a specially developed sampling apparatus, Schreiner et al. (1992) measured the CDD/CDF content of a flare combusting exhaust gases from an anaerobic sewage sludge digestor in Germany. The nozzle of the apparatus was moved through three cross-sections of the flame and cooling zone. The CDD/CDF content at the bottom of the flare was 1.4 pg I-TEQ_{DF}/Nm^3, 3.3. pg I-TEQ_{DF}/Nm^3 at the top of the flare, and 13.1 pg I-TEQ_{DF}/Nm^3 in the middle of the flare. Congener-specific results were not reported. Using the theoretical ratio of flare gas volume to digestor gas volume combusted, 78.6:1, and the average CDD/CDF content of the three measurements, 5.9 pg I-TEQ_{DF}/Nm^3, an emission rate of 0.46 ng I-TEQ_{DF}/Nm^3 of digestor gas combusted is yielded.

During 1996, POTWs in the United States treated approximately 122 billion liters of wastewater daily (U.S. EPA, 1997c). Although reliable data are not readily available on the amount of sewage sludge generated by POTWs that is subjected to stabilization by anaerobic digestion, a reasonable approximation is 25 percent of the total sludge generated (i.e., the sludge generated from treatment of about 30 trillion liters per day of wastewater). An estimated 196 kg of sludge solids are generated for every million liters of wastewater subjected to primary and secondary treatment (Water Pollution Control Federation, 1990). Thus, multiplying 30 billion liters per day (i.e., 25 percent of 122

billion liters) by 196 kg/million liters and 365 days/yr yields an annual estimate of 2 million metric tons of sludge solids that may be anaerobically digested in POTWs annually.

The volume of sludge digestor gas combusted in flares annually can be estimated using operation parameters for a "typical" anaerobic digestor system as described in Water Pollution Control Federation (1990). Multiplying the annual amount of sludge solids of 2 million metric tons by the following parameters and appropriate conversion factors yields an annual flared digestor gas volume of 467-million Nm^3:

- Fraction of total solids that are volatile solids = 75 percent;
- Reduction of volatile solids during digestion = 50 percent;
- Specific gas production = 0.94 m^3/kg volatile solids reduced; and
- Fraction of produced gas that is flared = 66 percent.

Because there are no direct measurements of CDD/CDF emissions from U.S. anerobic sludge digestor flares and because of uncertainties about the activity level for biogas combustion, no national emission estimate has been developed for inclusion in the national inventory. However, a preliminary estimate of the potential annual TEQ emissions from this source can be obtained by multiplying the emission factor of 0.46 ng I-TEQ_{DF}/Nm^3 of digestor gas flared by the estimated volume of gas flared annually in the United States, 467 million Nm^3. This calculation yields an annual potential release of 0.22 grams. This estimate should be regarded as a preliminary indication of possible emissions from this source category; further testing is needed to confirm the true magnitude of these emissions.

Table 3-1. Inventory of MSWIs in 1995 by Technology, APCD, and Annual Activity Level

MSWI		UNC	Hot ESP	Cold ESP	DSI/H-ESP	DS/FF	DS/CI/FF	DS/FF/ C-ESP	WS/FF	WS C-ESP	DS/C-ESP	DS/DSI/ C-ESP	DSI/ CI/ H-ESP	DSI/ C-ESP	DSI/ FF	DSI/ EGB	WS	Total
MB/RC	No. Facilities	0	0	2	0	2	0	0	0	0	0	0	0	6	2	0	0	12
	Activity Level, kg/yr	0	0	2.00E+08	0	1.14E+09	0	0	0	0	0	0	0	5.07E+08	2.59E+08	0	0	2.10E+09
MB/REF	No. Facilities	0	0	1	0	2	0	0	0	0	1	0	0	0	1	0	2	7
	Activity Level, kg/yr	0	0	1.69E+08	0	2.68E+08	0	0	0	0	4.22E+08	0	0	0	1.13E+08	0	2.04E+08	1.18E+09
MB/WW	No. Facilities	0	6	8	1	28	3	0	0	0	8	0	1	0	2	0	0	57
	Activity Level, kg/yr	0	1.04E+09	2.81E+09	4.22E+08	8.57E+09	1.17E+09	0	0	0	2.31E+09	0	2.75E+08	0	1.97E+08	0	0	1.68E+10
FB/RDF	No. Facilities	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	3
	Activity Level, kg/yr	0	0	0	0	1.69E+08	0	0	0	0	0	0	0	0	8.45E+07	1.13E+08	0	3.66E+08
RDF/Ded	No. Facilities	0	1	4	1	7	0	1	0	0	4	0	0	0	1	0	0	19
	Activity Level, kg/yr	0	4.22E+07	1.81E+09	2.00E+08	2.51E+09	0	5.63E+08	0	0	1.75E+09	0	0	0	4.22E+08	0	0	7.30E+09
MOD -SA	No. Facilities	9	4	4	0	0	0	0	1	0	0	1	0	0	1	0	3	23
	Activity Level, kg/yr	1.87E+08	1.82E+08	1.25E+08	0	0	0	0	2.82E+07	0	0	7.60E+07	0	0	3.24E+07	0	4.90E+07	6.80E+08
MOD-EA	No. Facilities	1	1	3	1	1	0	0	0	1	0	0	0	0	1	0	0	9
	Activity Level, kg/yr	1.41E+07	1.97E+07	8.28E+07	1.41E+07	1.18E+08	0	0	0	6.76E+07	0	0	0	0	1.01E+08	0	0	4.18E+08
Total	No. Facilities	10	12	22	3	41	3	1	1	1	13	1	1	6	9	1	5	130
Total	Activity Level, kg/yr	2.01E+08	1.29E+09	5.19E+09	**6.37E+08**	1.28E+10	1.17E+09	5.63E+08	2.82E+07	6.76E+07	4.49E+09	7.60E+07	2.75E+08	5.07E+08	1.21E+09	1.13E+08	2.53E+08	2.88E+10

Table 3-1. Inventory of MSWIs in 1995 by Technology, APCD, and Annual Activity Level (continued)

MB/RC = Mass Burn Rotary Kiln MB/REF = Mass Burn Refractory Walled MB/WW = Mass Burn Waterwalled RDF/Ded = Dedicated Refuse-Derived Fuel FB/RDF = Fluidized Bed Refuse-Derived Fuel MOD/SA = Modular Starved Air MOD/EA = Modular Excess Air	UNC = Uncontrolled Hot ESP = Hot side Electrostatic Precipitator Cold ESP = Cold side Electrostatic Precipitator DS/FF = Dry Scrubber with Fabric Filter FF = Fabric Filter EGB = Electro Gravel Bed WS = Wet Scrubber	DSI/FF = Dry Sorbent Injection with Fabric Filter DS/CI/FF = Spray Dryer - Carbon Injection - Fabric Filter DSI/EGB = Dry Sorbent Injection - Electro Gravel Bed

Table 3-2. Inventory of MSWIs in 1987 by Technology, APCD, and Annual Activity Level

	MSWI Type	UNC	Hot ESP	DS/FF	FF	EGB	WS	Total
MB/RC	No. of Facilities	0	3	0	1	0	0	4
	Activity Level,kg/yr	0	3.94E+08	0	1.58E+07	0	0	4.10E+08
MB/REF	No. of Facilities	0	12	1	0	0	7	20
	Activity Level,kg/yr	0	2.00E+09	1.41E+07	0	0	9.01E+08	3.04E+09
MB/WW	No. of Facilities	0	19	1	0	0	0	20
	Activity Level,kg/yr	0	5.20E+09	1.55E+08	0	0	0	5.35E+09
RDF/Dedicated	No. of Facilities	0	7	0	0	0	2	9
	Activity Level,kg/yr	0	3.01E+09	0	0	0	3.38E+08	3.35E+09
RDF/cofired	No. of Facilities	0	3	0	0	0	0	3
	Activity Level,kg/yr	0	2.53E+08	0	0	0	0	2.53E+08
MOD/SA	No. of Facilities	36	2	0	3	0	4	53
	Activity Level,kg/yr	5.73E+08	1.17E+08	0	1.43E+08	0	5.30E+07	1.15E+09
MOD/EA	No. of Facilities	2	0	0	0	1	1	4
	Activity Level,kg/yr	4.17E+07	0	0	0	6.76E+07	1.27E+08	2.36E+08
	Total No. of Facilities	38	54	2	4	1	14	113
	Total Activity Level,kg/yr	6.15E+08	1.12E+10	2.96E+08	1.59E+08	6.76E+07	1.42E+09	1.38E+10

Table 3-2. Inventory of MSWIs in 1987 by Technology, APCD, and Annual Activity Level (continued)

MB/RC = Mass Burn Rotary Kiln MB/REF = Mass Burn Refractory Walled MB/WW = Mass Burn Waterwalled RDF/Ded = Dedicated Refuse-Derived Fuel RDF/cofired = RDF cofired with coal MOD/SA = Modular Starved Air MOD/EA = Modular Excess Air	UNC = Uncontrolled Hot ESP = Hot side Electrostatic Precipitator DS/FF = Dry Scrubber with Fabric Filter FF = Fabric Filter EGB = Electro Gravel Bed WS = Wet Scrubber kg/y = kilogram per year

Table 3-3. CDD/CDF TEQ Emission Factors (ng TEQ per kg waste) for Municipal Solid Waste Incineration

Municipal Solid Waste Incinerator Design	Air Pollution Control Device	Average I-TEQ_{DF} Emission Factor (ng/kg)	Average TEQ_{DF}-WHO_{98} Emission Factor (ng/kg)	Basis and Rationale
Mass Burn Waterwall	C-ESP	6.10	6.54	Based on MB-WW; DS/C-ESP, same furnace and most similar APCD temperature
	DS/C-ESP	6.10	6.54	Based on direct tests
	DS/CI/FF	1.50	1.61	Based on direct tests
	DS/FF	0.63	0.72	Based on direct tests
	DSI/CI/H-ESP	7.74	8.22	Based on direct tests
	DSI/FF	1.91	2.07	Based on direct tests
	DSI/H-ESP	7.74	8.22	Based on MB-WW; DSI/CI/H-ESP, same furnace and most similar APCD temperature
	H-ESP	473	535	Based on direct tests
Mass Burn Refractory	C-ESP	236	254	Based on direct tests
	DS/C-ESP	51.1	53.2	Based on direct tests
	DS/FF	0.63	0.72	Based on MB-WW; DS/FF, most similar furnace and same APCD
	DSI/FF	1.91	2.07	Based on MB-WW; DSI/FF, most similar furnace and same APCD
	H-ESP	473	535	Based on MB-WW; H-ESP, most similar furnace and same APCD
	WS	236	254	Based on MB-Ref;C-ESP, same furnace and similar APCD temperature
Mass Burn Rotary Kiln	C-ESP	47.0	93.1	Based on MB-RK; DSI/FF, same furnace and similar emission control
	DS/FF	0.646	0.68	Based on direct tests
	DSI/C-ESP	47.0	93.1	Based on MB-RK; DSI/FF, same furnace and similar emission control
	DSI/FF	47.0	93.1	Based on direct tests
	FF	47.0	93.1	Based on MB-RK; DSI/FF, same furnace and similar emission control
	H-ESP	285	316	Based on direct tests
RDF Dedicated	C-ESP	231	253	Based on direct tests
	DS/C-ESP	0.53	0.56	Based on direct tests
	DS/FF	0.24	0.26	Based on direct tests
	DS/FF/C-ESP	0.24	0.26	Based on RDF-Ded; DS/FF, same furnace and similar APCD
	DSI/FF	231	253	Based on RDF-Ded; C-ESP, same furnace and similar emission control
	DSI/H-ESP	231	253	Based on RDF-Ded; C-ESP, same furnace and similar emission control
	H-ESP	1,492	1,679	Based on direct tests
	WS	231	253	Based on RDF-Ded; C-ESP, same furnace and similar APCD temperature

Table 3-3. CDD/CDF TEQ Emission Factors (ng TEQ per kg waste) for Municipal Solid Waste Incineration (continued)

Municipal Solid Waste Incinerator Design	Air Pollution Control Device	Average I-TEQ_{DF} Emission Factor (ng/kg)	Average TEQ_{DF}-WHO_{98} Emission Factor (ng/kg)	Basis and Rationale
Modular Starved-air	C-ESP	16.2	17.0	Based on Mod-EA; C-ESP, similar furnace (modular design) and same APCD
	DS/DSI/C-ESP	16.2	17.0	Based on Mod-EA; C-ESP, similar furnace (modular design) and similar emission control
	DSI/FF	0.025	0.024	Based on direct tests
	FF	16.2	17	Based on Mod-EA; C-ESP, similar furnace (modular design) and similar emission control
	H-ESP	79.0	85.7	Based on direct tests
	UNC	0.025	0.024	Based on Mod-SA; DSI/FF, same furnace and most similar expected emissions
	WS	16.2	17.0	Based on Mod-EA; C-ESP, similar furnace (modular design) and similar APCD temperature
	WS/FF	16.2	17.0	Based on Mod-EA; C-ESP, similar furnace (modular design) and similar APCD temperature
Modular Excess-air	C-ESP	16.2	17.0	Based on direct tests
	DS/FF	16.2	17.0	Based on Mod-EA; C-ESP, same furnace and similar temperature in APCD - may over-estimate emissions
	DSI/FF	0.025	0.024	Based on Mod-SA; DSI/FF, similar (modular design) furnace and same APCD
	DSI/H-ESP	118	119	Based on Mod-EA; H-ESP, same furnace and similar emissions
	EGB	0.025	0.024	Based on Mod-SA; DSI/FF, same furnace and most similar expected emissions
	H-ESP	118	119	Based on direct tests
	UNC	0.025	0.024	Based on Mod-SA; DSI/FF, same furnace and most similar expected emissions
	WS	16.2	17.0	Based on Mod-EA; C-ESP, same furnace and similar APCD temperature
	WS/C-ESP	16.2	17.0	Based on Mod-EA; C-ESP, same furnace and similar APCD
Fluidized-bed RDF	DS/FF	0.63	0.72	Based on MB-WW; DS/FF, similar furnace and same APCD
	DSI/EGB	0.63	0.72	Based on MB-WW; DS/FF, similar furnace - may under-estimate emissions
	DSI/FF	0.63	0.72	Based on MB-WW; DS/FF, similar furnace - may under-estimate emissions

Key:
- ng/kg = Nanograms TEQ per kilograms waste
- DS/FF = Dry scrubber combined with a fabric filter
- DSI/FF = Dry sorbent injection coupled with a fabric filter
- DS/CI/FF = Dry scrubber coupled with carbon injection and a fabric filter
- C-ESP = Cold-sided electrostatic precipitator (temperature at control device is below $\leq$ 230°C
- H-ESP = Hot-sided electrostatic precipitator (temperature at control device is above $\geq$ 230°C
- WS = Wet scrubber
- UNC = Uncontrolled (no APCD)

Table 3-4a. Annual I-TEQ$_{DF}$ Emissions (g/yr) from MSWIs Operating in 1995

Municipal Solid Waste Incinerator Design	Air Pollution Control Device	I-TEQ$_{DF}$ Emissions from Tested Facilities (g TEQ/yr)	Average I-TEQ$_{DF}$ Emission Factor (ng/kg)	Activity Level Non-Tested Facilities (kg/yr)	I-TEQ$_{DF}$ Emissions from Non-Tested Facilities (g TEQ/yr)	Total I-TEQ$_{DF}$ Emissions from All Facilities (g TEQ/yr)
Mass Burn Waterwall	C-ESP	0	6.10	2.81e+09	17.1	17.1
	DS/C-ESP	2.09	6.10	1.88e+09	11.4	13.5
	DS/CI/FF	0.635	1.50	7.44e+08	1.12	1.75
	DS/FF	2.01	0.63	5.98e+09	3.77	5.77
	DSI/CI/H-ESP	2.12	-	0	0	2.12
	DSI/FF	0.279	-	0	0	0.279
	DSI/H-ESP	0	7.74	4.22e+08	3.27	3.27
	H-ESP	163	473	1.79e+08	84.5	247
	Subtotal	170			121	291
Mass Burn Refractory	C-ESP	39.8	-	0	0	39.8
	DS/C-ESP	21.6	-	0	0	21.6
	DS/FF	0	0.63	2.68e+08	0.168	0.168
	DSI/FF	0	1.91	1.13e+08	0.216	0.216
	WS	0	236	2.04e+08	48.1	48.1
	Subtotal	61.4			48.5	110
Mass Burn Rotary Kiln	C-ESP	0	47.0	2.00e+08	9.4	9.4
	DS/FF	0.245	0.646	7.57e+08	0.489	0.734
	DSI/C-ESP	0	47.0	5.07e+08	23.8	23.8
	DSI/FF	5.29	47.0	1.46e+08	6.85	12.1
	Subtotal	5.54			40.6	46.1
RDF Dedicated	C-ESP	32.5	231	1.67e+09	385	418
	DS/C-ESP	0.321	0.53	1.14e+09	0.603	0.924
	DS/FF	0.0975	0.24	1.58e+09	0.379	0.477
	DSI/FF	0	231	4.22e+08	97.6	97.6
	DSI/H-ESP	0	231	2.00e+08	46.2	46.2
	H-ESP	0	1,492	4.22e+07	63	63
	DS/FF/C-ESP	0	0.24	5.63e+08	0.135	0.135
	Subtotal	33			593	626
Modular Starved-air	C-ESP	0	16.2	1.25e+08	2	2
	DSI/FF	0.000801	-	0	0	0.000801
	H-ESP	8.01	79.0	8.03e+07	6.34	14.4
	UNC	0	0.025	1.87e+08	0.00463	0.00463
	WS	0	16.2	4.90e+07	0.785	0.785
	WS/FF	0	16.2	2.82e+07	0.451	0.451
	DS/DSI/C-ESP	0	16.2	7.60e+07	1.22	1.22
	Subtotal	8.01			10.8	18.8
Modular Excess-air	C-ESP	0.0643	16.2	6.25e+07	1	1.07
	DS/FF	0	16.2	1.18e+08	1.9	1.9
	DSI/FF	0	0.025	1.01e+08	0.00251	0.00251
	DSI/H-ESP	0	118	1.41e+07	1.66	1.66
	H-ESP	2.32	-	0	0	2.32
	UNC	0	0.025	1.41e+07	0.000348	0.000348
	WS/C-ESP	0	16.2	6.76e+07	1.08	1.08
	Subtotal	2.39			5.64	8.03
Fluidized-bed RDF	DS/FF	0	0.63	1.69e+08	0.106	0.106
	DSI/EGB	0	0.63	1.13e+08	0.0709	0.0709
	DSI/FF	0	0.63	8.45e+07	0.0532	0.0532
	Subtotal	0			0.231	0.231
Total		280			820	1,100

Key: DS/FF = Dry Scrubber combined with a Fabric Filter
DSI/FF = Dry Sorbent Injection coupled with a Fabric Filter
DS/CI/FF = Dry Scrubber -Carbon Injection-Fabric Filter
C-ESP = Cold-side Electrostatic Precipitator (Temperature at control device is below ≤230°C)
H-ESP = Hot-side Electrostatic Precipitator (Temperature at control device is ≥230°C)
WS = Wet Scrubber
UNC = Uncontrolled (no APCD)
EGB = Electro Granular Activated Carbon Bed
ng/kg = nanogram per kilogram
kg/yr = kilograms per year

Table 3-4b. Annual TEQ_{DF}-WHO_{98} Emissions (g/yr) from MSWIs Operating in 1995

Municipal Solid Waste Incinerator Design	Air Pollution Control Device	TEQ_{DF}-WHO_{98} Emissions from Tested Facilities (g TEQ/yr)	Average TEQ_{DF}-WHO_{98} Emission Factor (ng/kg)	Activity Level Non-Tested Facilities (kg/yr)	TEQ_{DF}-WHO_{98} Emissions from Non-Tested Facilities (g TEQ/yr)	Total TEQ_{DF}-WHO_{98} Emissions from All Facilities (g TEQ/yr)
Mass Burn Waterwall	C-ESP	0	6.54	2.81e+09	18.4	18.4
	DS/C-ESP	2.24	6.54	1.88e+09	12.3	14.54
	DS/CI/FF	0.68	1.61	7.44e+08	1.20	1.88
	DS/FF	2.10	0.72	5.98e+09	4.04	6.14
	DSI/CI/H-ESP	2.26	-	0	0	2.26
	DSI/FF	0.30	-	0	0	0.30
	DSI/H-ESP	0	8.22	4.22e+08	3.47	3.47
	H-ESP	183	535	1.79e+08	94.7	278
	Subtotal	191			134	325
Mass Burn Refractory	C-ESP	43.0	-	0	0	43.0
	DS/C-ESP	22.5	-	0	0	22.5
	DS/FF	0	0.72	2.68e+08	0.181	0.181
	DSI/FF	0	2.07	1.13e+08	0.234	0.234
	WS	0	254	2.04e+08	51.9	51.9
	Subtotal	65.4			52.3	117.8
Mass Burn Rotary Kiln	C-ESP	0	93.1	2.00e+08	18.6	18.6
	DS/FF	0.265	0.68	7.57e+08	0.53	0.80
	DSI/C-ESP	0	93.1	5.07e+08	47.2	47.2
	DSI/FF	10.5	93.1	1.46e+08	13.6	24.1
	Subtotal	10.8			80.0	90.8
RDF Dedicated	C-ESP	35.6	253	1.67e+09	422	458
	DS/C-ESP	0.34	0.56	1.14e+09	0.638	0.98
	DS/FF	0.10	0.26	1.58e+09	0.405	0.50
	DSI/FF	0	253	4.22e+08	107	107
	DSI/H-ESP	0	253	2.00e+08	50.6	50.6
	H-ESP	0	1,679	4.22e+07	70.9	70.9
	DS/FF/C-ESP	0	253	5.63e+08	0.144	0.144
	Subtotal	36.1			651	687
Modular Starved-air	C-ESP	0	17.0	1.25e+08	2.12	2.12
	DSI/FF	0.0008	-	0	0	0.0008
	H-ESP	8.69	85.7	8.03e+07	6.88	15.57
	UNC	0	0.024	1.87e+08	0.005	0.005
	WS	0	17.0	4.90e+07	0.832	0.832
	WS/FF	0	17.0	2.82e+07	0.478	0.478
	DS/DSI/C-ESP	0	17.0	7.60e+07	1.29	1.29
	Subtotal	8.69			11.6	20.3
Modular Excess-air	C-ESP	0.068	17.0	6.25e+07	1.06	1.13
	DS/FF	0	17.0	1.18e+08	2.01	2.01
	DSI/FF	0	0.024	1.01e+08	0.002	0.002
	DSI/H-ESP	0	119	1.41e+07	1.68	1.68
	H-ESP	2.35	-	0	0	2.35
	UNC	0	0.024	1.41e+07	0.003	0.003
	WS/C-ESP	0	17.0	6.76e+07	1.15	1.15
	Subtotal	2.42			5.90	8.32
Fluidized-bed RDF	DS/FF	0	0.72	1.69e+08	0.114	0.114
	DSI/EGB	0	0.72	1.13e+08	0.076	0.076
	DSI/FF	0	0.72	8.45e+07	0.057	0.057
	Subtotal	0			0.247	0.247
Total		315		935		1,250

Key: DS/FF = Dry Scrubber combined with a Fabric Filter
DSI/FF = Dry Sorbent Injection coupled with a Fabric Filter
DS/CI/FF = Dry Scrubber -Carbon Injection-Fabric Filter
C-ESP = Cold-side Electrostatic Precipitator (Temperature at control device is below ≤230°C)
H-ESP = Hot-side Electrostatic Precipitator (Temperature at control device is ≥230°C)
WS = Wet Scrubber
UNC = Uncontrolled (no APCD)
EGB = Electro Granular Activated Carbon Bed
ng/kg = nanogram per kilogram
kg/yr = kilograms per year

Table 3-5a. Annual I-TEQ$_{DF}$ Emissions to the Air From MSWIs Operating in 1987

Municipal Solid Waste Incinerator Design	Air Pollution Control Device	I-TEQ$_{DF}$ Emissions fromTested Facilities (g TEQ/yr)	Average I-TEQ$_{DF}$ Emission Factor (ng/kg)	Activity Level Non-Tested Facilities (kg/yr)	I-TEQ$_{DF}$ Emissions from Non-Tested Facilities (g TEQ/yr)	Total I-TEQ$_{DF}$ Emissions from All Facilities (g TEQ/yr)
Mass Burn Waterwall	DS/FF	0.0373	-	0	0	0.0373
	H-ESP	433	473	3.27e+09	1550	1980
	Subtotal	433			1550	1980
Mass Burn Refractory	DS/FF	0	0.63	1.41e+08	0.0887	0.0887
	H-ESP	0	473	2.00e+09	944	944
	WS	0	236	9.01e+08	212	212
	Subtotal	0			1,160	1,160
Mass Burn Rotary Kiln	FF	0	47.0	1.58e+07	0.741	0.741
	H-ESP	48.2	285	2.25e+08	64.2	112
	Subtotal	48.2			65	113
RDF Dedicated	H-ESP	840	1492	2.45e+09	3660	4500
	WS	0	231	3.38e+08	78.1	78.1
	Subtotal	840			3730	4570
RDF Cofired	H-ESP	0	231	2.53e+08	58.6	58.6
Modular Starved-air	FF	0	16.2	1.43e+08	2.29	2.29
	H-ESP	0.0643	79.0	3.61e+08	28.5	28.5
	UNC	0	0.025	5.73e+08	0.0142	0.0142
	WS	0	16.2	5.30e+07	0.848	0.848
	Subtotal	0.0643			31.6	31.7
Modular Excess-air	EGB	0	0.025	6.76e+07	0.0017	0.0017
	UNC	0	0.025	4.17e+07	0.0010	0.0010
	WS	0	16.2	1.27e+08	2.03	2.03
	Subtotal	0			2.03	2.03
Totals		1,320			6,590	7,915

Key: DS/FF = Dry Scrubber combined with a Fabric Filter
DSI/FF = Dry Sorbent Injection coupled with a Fabric Filter
DS/CI/FF = Dry Scrubber -Carbon Injection-Fabric Filter
C-ESP = Cold-side Electrostatic Precipitator (Temperature at control device is below $\leq$230°C)
H-ESP = Hot-side Electrostatic Precipitator (Temperature at control device is $\geq$230°C)
WS = Wet Scrubber
UNC = Uncontrolled (no APCD)
EGB = Electro Granular Activated Carbon Bed
ng/kg = nanogram per kilogram
kg/yr = kilograms per year

Table 3-5b. Annual TEQ_{DF}-WHO_{98} Emissions to the Air From MSWIs Operating in 1987

Municipal Solid Waste Incinerator Design	Air Pollution Control Device	TEQ_{DF}-WHO_{98} Emissions fromTested Facilities (g TEQ/yr)	Average TEQ_{DF}-WHO_{98} Emission Factor (ng/kg)	Activity Level Non-Tested Facilities (kg/yr)	TEQ_{DF}-WHO_{98} Emissions from Non-Tested Facilities (g TEQ/yr)	Total TEQ_{DF}-WHO_{98} Emissions from All Facilities (g TEQ/yr)
Mass Burn Waterwall	DS/FF	0.039	-	0	0	0.039
	H-ESP	485	535	3.27e+09	1,732	2,218
	Subtotal	485			1,732	2,218
Mass Burn Refractory	DS/FF	0	0.72	1.41e+08	0.095	0.095
	H-ESP	0	535	2.00e+09	1,058	1,058
	WS	0	254	9.01e+08	229	229
	Subtotal	0			1,287	1,287
Mass Burn Rotary Kiln	FF	0	93.1	1.58e+07	1.47	1.47
	H-ESP	53.4	316	2.25e+08	71.2	124.6
	Subtotal	53.4			72.7	126.1
RDF Dedicated	H-ESP	946	1,679	2.45e+09	4,114	5,060
	WS	0	253	3.38e+08	85.5	85.5
	Subtotal	946			4,200	5,146
RDF Cofired	H-ESP	0	253	2.53e+08	64.1	64.1
Modular Starved-air	FF	0	17.0	1.43e+08	2.43	2.43
	H-ESP	0.068	85.7	3.61e+08	30.9	31.0
	UNC	0	0.024	5.73e+08	0.014	0.014
	WS	0	17.0	5.30e+07	0.898	0.898
	Subtotal	0.068			34.2	34.3
Modular Excess-air	EGB	0	0.024	6.76e+07	0.0016	0.0016
	UNC	0	0.024	4.17e+07	0.0010	0.0010
	WS	0	17.0	1.27e+08	2.15	2.15
	Subtotal	0			2.15	2.15
Totals		1,485			7,392	8,877

Key: DS/FF = Dry Scrubber combined with a Fabric Filter
DSI/FF = Dry Sorbent Injection coupled with a Fabric Filter
DS/CI/FF = Dry Scrubber -Carbon Injection-Fabric Filter
C-ESP = Cold-side Electrostatic Precipitator (Temperature at control device is below ≤230°C)
H-ESP = Hot-side Electrostatic Precipitator (Temperature at control device is ≥230°C)
WS = Wet Scrubber
UNC = Uncontrolled (no APCD)
EGB = Electro Granular Activated Carbon Bed
ng/kg = nanogram per kilogram
kg/yr = kilograms per year

Table 3-6. Fly Ash from a Municipal Incinerator
(Concentrations in μg/kg)

Congener Group	Average Concentration	Concentration Range
TCDD	3.7	1.6 - 12
PeCDD	6.4	2.0 - 25
HxCDD	9.1	1.5 - 42
HpCDD	2.3	0.5 - 9.2
OCDD	1.5	0.2 - 6.0
TOTAL CDDs	**23**	**6.2 - 94**
TCDF	12	5.1 - 36
PeCDF	17	8.3 - 40
HxCDF	14	3.9 - 40
HpCDF	2.9	0.8 - 9.2
OCDF	1.2	ND - 2.1
TOTAL CDFs	**47**	**22 - 110**

Table 3-7. Comparison of the Amount of TEQs Generated Annually in MSWI Ash

Data Source	Type of Ash	Mean Total CDD/CDF Concentration (ng/kg)	Mean I-TEQ_{DF} (ng/kg)	Annual TEQ Amount 1995 Value[a] (g I-TEQ_{DF}/yr)	Annual TEQ Amount 1987 Value[a] (g I-TEQ_{DF}/yr)
USEPA, 1990c	Mixed	12,383	258	1,806	1,290
Washington, 1998					
Ft. Lewis	Bottom	0	0	0	0
	Fly	71,280	4,980	3,486	2,490
Bellingham	Mixed	1,884	38	266	190
Spokane	Mixed	1,414	163	1,141	815
	Fly	10,320	510	357	255
	Bottom	100	0.1	1	0.05
Shane, 1990	Fly	175,000	-	-	-
Clement, 1988	Fly	70,000	-	-	-
USEPA, 1987a					
North America	Fly	1,286,000	-	-	-
Europe	Fly	876,000	-	-	-
Japan	Fly	2,600	-	-	-
Wire Reclamation	Fly	12,010	-	-	-
	Bottom	1,310	-	-	-
Lahl, 1991	Mixed	177,640	-	-	-

- Indicates that values could not be calculated.

a. In calculating the Annual TEQ Amounts, fly ash and bottom ash were considered to be 10% and 90% of the total ash, respectively.

Table 3-8. CDD/CDF Emission Factors for Hazardous Waste Incinerators and Boilers

Congener/Congener Group	Incinerator Average Mean emission factor (17 facilities) (ng/kg feed)		Hot-Side ESP Boilers Mean emission factor (2 facilities) (ng/kg feed)	
	Nondetects Set to 1/2 Det. Limit	Nondetects Set to Zero	Nondetects Set to 1/2 Det. Limit	Nondetects Set to Zero
2,3,7,8-TCDD	0.44	0.14	0.10	0.00
1,2,3,7,8-PeCDD	0.18	0.14	0.11	0.04
1,2,3,4,7,8-HxCDD	0.22	0.18	0.15	0.08
1,2,3,6,7,8-HxCDD	0.32	0.28	0.20	0.18
1,2,3,7,8,9-HxCDD	0.49	0.48	0.22	0.20
1,2,3,4,6,7,8-HpCDD	1.77	1.74	1.17	1.17
OCDD	4.13	3.74	5.24	5.24
2,3,7,8-TCDF	2.96	2.69	0.81	0.81
1,2,3,7,8-PeCDF	2.36	2.33	0.38	0.38
2,3,4,7,8-PeCDF	2.56	2.51	0.52	0.52
1,2,3,4,7,8-HxCDF	9.71	9.71	0.83	0.83
1,2,3,6,7,8-HxCDF	3.95	3.95	0.37	0.37
1,2,3,7,8,9-HxCDF	0.31	0.29	0.08	0.02
2,3,4,6,7,8-HxCDF	2.70	2.70	0.56	0.56
1,2,3,4,6,7,8-HpCDF	16.87	16.68	1.04	0.93
1,2,3,4,7,8,9-HpCDF	1.74	1.71	0.18	0.16
OCDF	13.79	13.46	0.70	0.70
Total I-TEQ_{DF}	4.22	3.83	0.78	0.64
Total TEQ_{DF}-WHO_{98}	4.29	3.88	0.83	0.65
Total TCDD	NR	NR	0.77	0.77
Total PeCDD	NR	NR	1.15	0.77
Total HxCDD	NR	NR	1.67	1.62
Total HpCDD	NR	NR	2.34	2.34
Total OCDD	4.13	3.74	5.24	5.24
Total TCDF	NR	NR	5.47	5.47
Total PeCDF	NR	NR	5.51	5.51
Total HxCDF	NR	NR	4.04	4.04
Total HpCDF	NR	NR	1.94	1.94
Total OCDF	13.78	13.46	0.70	0.70
Total CDD/CDF	153	153	28.83	28.39

ng/kg = nanograms per kilogram
NR = not reported

Source: U.S. EPA (1996c).

Table 3-9. Summary of Annual Operating Hours for Each MWI Type

MWI Type	Capacity Ranges (lb/hr)	Annual Charging Hours (hr/yr)	Maximum Annual Charging Hours (hr/yr)	Capacity Factor
Continuous commercial	>1,000	7,776	8,760	0.89
Continuous onsite	501 - 1,000 >1,000	1,826 2,174	5,475	0.33 0.40
Intermittent	≤ 500	1,250	4,380	0.29
Batch	Case by case	Case by case		Case by case

lb/hr = pounds per hour
hr/yr = hours per year

Table 3-10. OAQPS Approach: PM Emission Limits for MWIs and Corresponding Residence Times in the Secondary (2°) Combustion Chamber

MWI Type	PM Emission Limit[a] (gr/dscf)	Residence Time in 2° Chamber (seconds)	I-TEQ_{DF} Emission Factor (kg I-TEQ_{DF}/kg waste)
Intermittent and Continuous	≥0.3	0.25	3.96e-9
	0.16 to < 0.30	1.0	9.09e-10
	0.10 to ≤0.16	2.0	7.44e-11
Batch	≥0.079	0.25	3.96e-9
	0.042 to <0.079	1.0	9.09e-10
	0.026 to <0.042	2.0	7.44e-11

[a] gr/dscf = grains per dry standard cubic foot at standard temperature and pressure.

Table 3-11. OAQPS Approach: Estimated Nationwide I-TEQ$_{DF}$ Emissions (g/yr) for 1995

MWI Type	Residence Time or APCD	CDD/CDF Emission Factor (ng/kg)	I-TEQ$_{DF}$ Emission Factor (ng/kg)	Activity Level (kg/yr)	CDD/CDF Emissions (g/yr)	I-TEQ$_{DF}$ Emissions (g/yr)
Batch	0.25 sec	193,997	3,960	5.95e+06	1.15e+03	2.36e+01
	1.00 sec	44,500	909	4.20e+05	1.87e+01	3.82e-01
	2.00 sec	3,650	74	2.14e+05	7.81e-01	1.58e-02
Continuous	0.25 sec	193,997	3,960	1.20e+06	2.33e+02	4.75e+00
	1.00 sec	44,500	909	5.10e+06	2.27e+02	4.64e+00
	2.00 sec	3,650	74	3.01e+07	1.10e+02	2.23e+00
Continuous/ Intermittent	0.25 sec	193,997	3,960	4.54e+06	8.81e+02	1.80e+01
	1.00 sec	44,500	909	5.10e+06	2.27e+02	4.64e+00
	2.00 sec	3,650	74	9.79e+07	3.57e+02	7.24e+00
Intermittent	0.25 sec	193,997	3,960	4.18e+06	8.11e+02	1.66e+01
	1.00 sec	44,500	909	5.57e+07	2.48e+03	5.06e+01
	2.00 sec	3,650	74	4.31e+07	1.57e+02	3.19e+00
Subtotal: Uncontrolled				2.54e+08	6.66e+03	1.36e+02
Batch	Wet Scrubber	426	10	2.42e+04	1.03e-02	2.42e-04
Continuous	Wet Scrubber	426	10	1.88e+08	8.01e+01	1.88e+00
Continuous/ Intermittent	Wet Scrubber	426	10	1.22e+08	5.20e+01	1.22e+00
Intermittent	Wet Scrubber	426	10	6.04e+07	2.57e+01	6.04e-01
Subtotal: Controlled w/Wet Scrubber				3.70e+08	1.58e+02	3.70e+00
Continuous	Dry Scrubber - no carbon	365	7	9.94e+07	3.63e+01	6.96e-01
Continuous/ Intermittent	Dry Scrubber - no carbon	365	7	7.86e+06	2.87e+00	5.50e-02
Intermittent	Dry Scrubber - no carbon	365	7	2.07e+07	7.56e+00	1.45e-01
Continuous	Dry Scrubber - with carbon	70	2	1.43e+07	1.00e+00	2.86e-02
Continuous/ Intermittent	Dry Scrubber - with carbon	70	2	3.70e+06	2.59e-01	7.40e-03
Subtotal: Controlled w/Dry Scrubber				1.46e+08	4.80e+01	9.32e-01
Intermittent	Fabric Filter/ Packed Bed	33,400	681	6.99e+05	2.34e+01	4.76e-01
Total MWI				7.71e+08	6.88e+03	1.41e+02

NA = Not applicable
ng/kg = nanograms per kilogram
kg/yr = kilograms per year
g/yr = grams per year

Table 3-12. AHA Approach: I-TEQ$_{DF}$ Emission Factors Calculated for Air Pollution Control

APC Category	I-TEQ$_{DF}$ Emission Factor (lb/10^6 lbs waste)	Number of MWI Test Reports Used[a]
Uncontrolled		
MWIs up to 200 lb/hr	1.53e-03	4
MWIs > 200 lb/hr	5.51e-04	13
Wet scrubber/BHF/ESP[b]	4.49e-05	11
Dry sorbent injection/Fabric Filter	6.95e-05	8

[a] The same MWI may have been used more than once in deriving emission factors.

[b] Wet scrubbers-bag house filters-electrostatic precipitators. Bag house is also called Fabric Filter.

Source: Doucet (1995).

Table 3-13. AHA Assumptions of the Percent Distribution of Air Pollution Control on MWIs Based on PM Emission Limits

PM Emission Limits[a] (gr/dscf)	Percent MWIs Uncontrolled[b]	Percent MWIs with Scrubbers/ BHFs/ESPs[c]	Percent MWIs DI/FF[d]
≥ 0.10	50%	50%	0%
0.08 to < 0.10	25%	75%	0%
0.03 to < 0.08	0%	98%	2%
< 0.03	0%	30%	70%

[a] Particulate matter (PM) emission limits at the stack, grains per dry standard cubic foot (gr/dscf).

[b] Uncontrolled means there is no air pollution control device installed on the MWI.

[c] Scrubbers/BHFs/ESPs means wet scrubbers/bag house filters/electrostatic precipitators.

[d] DI/FF means dry sorbent injection combined with fabric filters.

Table 3-14. AHA Approach: Estimated Annual Nationwide I-TEQ$_{DF}$ Emissions

APCD[a]	MWI Capacity[b] (lb/hr)	I-TEQ$_{DF}$ Emission Factor[c] (g/kg waste)	MWI Activity Level[d] (kg/yr)	Annual I-TEQ$_{DF}$ Emissions (g/yr)
Uncontrolled	≤ 200 > 200	1.54 e-06 5.51 e-07	2.28 e+07 1.54 e+08	3.51e+01 8.48e+01
Subtotal: Uncontrolled			1.77 e+08	1.20e+02
WS/BHF/ESP	>200	4.49 e-08	3.51 e+08	1.58e+01
DI/FF	>200	6.95 e-08	2.60 e+07	1.81
Subtotal: Controlled			3.77 e+08	1.76e+01
Total			5.54 e+08	1.38e+02

[a] APCD = Air Pollution Control Device assumed by AHA. Uncontrolled means there is no air pollution control device installed on the MWI. WS/BHF/ESP = Wet scrubber-bag house filter-electrostatic precipitator. DI/FF = Dry sorbent injection-fabric filter.

[b] MWI capacity is the design capacity of the primary combustion chamber.

[c] I-TEQ$_{DF}$ Emission Factor derived from tested facilities.

[d] Activity Level is the annual amount of medical waste incinerated by each APCD class.

lb/hr = pounds per hour
g/kg = grams per kilogram
kg/yr = kilograms per year
g/yr = grams per year

Table 3-15. Comparison Between Predicted Residence Times and Residence Times Confirmed by State Agencies in EPA/ORD Telephone Survey

State	Residence Time Categories	Percentage of Uncontrolled MWIs Predicted by PM Method	Percentage of Uncontrolled MWIs Confirmed by State Agency
Michigan	1/4 second 1.0 second 2.0 seconds	2% (6/280 MWIs) 2% (5/280) 96% (269/280)	96% (269/280 MWIs) 3% (9/280) 1% (1/280)
Massachusetts	1/4 second 1.0 second 2.0 seconds	6% (6/94 MWIs) 0% (0/94) 94% (88/94)	Unknown Unknown 4% (2/50)
Virginia	1/4 second 1.0 second 2.0 seconds	11% (6/56) 0 % (0/50) 89% (50/56)	4.5% (1/22) 91% (20/22) 4.5% (1/22)
New Jersey	1/4 second 1.0 second 2.0 seconds	0% (0/53 MWIs) 0% (0/53) 100% (53/53)	Unknown Unknown Unknown

Source: O'Rourke (1996).

Table 3-16. EPA/ORD Approach: TEQ Emissions from Medical Waste Incineration for Reference Year 1995

MWI Class (APCD)	MWI Subclass (Capacity or APCD)	No. of Tested Facilities	Total CDD/CDF Emission Factor (ng/kg)	I-TEQ_{DF} Emission Factor (ng/kg)	TEQ_{DF}-WHO_{98} Emission Factor (ng/kg)	Activity Level (kg/yr)	Annual CDD/CDF Emissions (g/yr)	Annual I-TEQ_{DF} Emissions (g/yr)	Annual TEQ_{DF}-WHO_{98} Emissions (g/yr)
Uncontrolled	≤200 lb/hr	3	9.25e+04	1.86e+03	1.98e+03	3.06e+07	2.83e+03	5.71e+01	6.06e+01
	>200 lb/hr	5	6.05e+04	1.68e+03	1.78e+03	2.23e+08	1.35e+04	3.75e+02	3.98e+02
Controlled	Wet Scrubber/ Fabric Filter/ ESP	9	4.67e+03	7.22e+01	7.43e+01	3.71e+08	1.73e+03	2.68e+01	2.76e+01
	Dry Sorbent Injection/ Fabric Filter	2	2.85e+02	6.78	6.86	1.46e+08	4.16e+01	9.90e-01	1.00e+00
	Fabric Filter/ Packed Bed Scrubber	1	1.11e+05	1.35e+03	1.49e+03	6.99e+05	7.76e+01	9.44e-01	1.04e+00
Total						7.71e+08	1.82e+04	4.61e+02	4.88e+02

APCD = Air Pollution Control Devices
ng/kg = nanograms per kilogram
kg/yr = kilograms per year
g/yr = grams per year
lb/hr = pounds per hour

Table 3-17. Summary of Annual TEQ Emissions from Medical Waste Incineration (MWI) for Reference Year 1987

MWI Class[a]	No. of Tested Facilities	Total CDD/CDF Emission Factor[b] (g/kg)	I-TEQ_{DF} Emission Factor (g/kg)	TEQ_{DF}-WHO_{98} Emission Factor (g/kg)	Activity Level (kg/yr)	Annual CDD/CDF Emissions (g/yr)	Annual I-TEQ_{DF} Emissions (g/yr)	Annual TEQ_{DF}-WHO_{98} Emissions (g/yr)
≤ 200 lb/hr	3	9.25e-05	1.86e-06	1.98e-06	2.19e+08	2.02e+04	4.08e+02	4.34e+02
> 200 lb/hr	5	6.05e-05	1.68e-06	1.78e-06	1.21e+09	7.32e+04	2.03e+03	2.15e+03
Total	8				1.43e+09	9.34e+04	2.44e+03	2.59e+03

[a] This uses the categorization scheme of the AHA Approach (Doucet, 1995).

kg/yr = kilograms per year
g/kg = grams per kilogram
g/yr = grams per year
lb/hr = pounds per hour

Table 3-18. Comparison of Basic Assumptions Used in the EPA/ORD, the EPA/OAQPS, and the AHA Approaches to Estimating Nationwide CDD/CDF TEQ Emissions from MWIs in 1995

Assumptions	EPA/ORD Approach	EPA/OAQPS Approach	AHA Approach
Reference Year	1995	1995	1995
Number of MWIs	2,375	2,375	2,233
Estimated Activity Level	7.71 e+08 kg/yr	7.71 e+08 kg/yr	5.54 e+08 kg/yr
Percent of Activity Level at Uncontrolled MWIs	33%	33%	32%
Percent of Activity Level at Controlled MWIs	67%	67%	68%
Subclassification of Uncontrolled Class	Same as AHA assumption	By residence times (RT) in secondary chamber	By design capacity
Assumed Distribution of Uncontrolled Class	Same as AHA assumption	By RT of 0.25, 1.0 and 2.0 sec by State PM emission limits	By estimated annual hrs of operation of <200 lb/hr and >200 lb/hr design capacity
APCDs Assumed for Controlled Class	WS/FF/ESP DI/FF FF/Packed Bed Scrub	WS DS-no Carbon DS-Carbon FF/Packed Bed Scrub	WS/FF/ESP DI/FF
Assumed Distribution of Controls	Yes/ Analogous to AHA method.	Yes/ Analogous to AHA method	Yes/ Based on survey and State PM emission limits
Emission Factor Approach Used	Yes	Yes	Yes
No. of Tested MWIs Used to Develop Emission Factors	Uncontrolled: 8 Controlled: 11	Uncontrolled: 10 Controlled: 23	Uncontrolled: 13 Controlled: 12
Uncontrolled I-TEQ_{DF} Emission Factors (ng/kg)	1,865 = ≤200 lb/hr 1,680 = >200 lb/hr	a/ 3,960 = 0.25 s RT b/ 909 = 1.0 s RT c/ 74 =2.0 s RT	d/ 1,540 =≤200 lb/hr e/ 551= > 200 lb/hr
Controlled I-TEQ_{DF} Emission Factors (ng/kg)[f]	WS/FF/ESP: 72.2 DSI/FF: 6.8 FF/PBS: 1,350	WS: 10 DS no carbon: 7 DS with carbon: 2 FF/PBS: 681	WS/FF/ESP: 44.9 DSI/FF: 69.5

WS = Wet Scrubber; FF = Fabric Filter; ESP = Electrostatic Precipitator; DSI = Dry Sorbent Injection; DS = Dry Scrubber; no carbon = without the addition of activated carbon; with carbon = with the addition of activated carbon; PBS = Packed Bed Scrubber.

a 0.25 seconds (s) residence time (RT) in the secondary chamber.

b 1.0 seconds (s) residence time (RT) in the secondary chamber.

c 2.0 seconds (s) residence time (RT) in the secondary chamber.

d design capacities less than or equal to 200 lbs/hr.

e design capacities greater than 200 lbs/hr.

f emission factors as reported in Tables 3-9, 3-12, and 3-14.

lb/hr = pounds per hour

kg/yr = kilograms per year

Table 3-19. CDD/CDF Air Emission Factors for a Crematorium

Congener/Congener Group	Mean Facility Emission Factor	
	Assuming ND = zero (ng/body)	Assuming ND = 1/2 det limit (ng/body)
2,3,7,8-TCDD	28.9	28.9
1,2,3,7,8-PeCDD	89.6	89.6
1,2,3,4,7,8-HxCDD	108	108
1,2,3,6,7,8-HxCDD	157	157
1,2,3,7,8,9-HxCDD	197	197
1,2,3,4,6,7,8-HpCDD	1,484	1,484
OCDD	2,331	2,331
2,3,7,8-TCDF	206	206
1,2,3,7,8-PeCDF	108	117
2,3,4,7,8-PeCDF	339	349
1,2,3,4,7,8-HxCDF	374	374
1,2,3,6,7,8-HxCDF	338	338
1,2,3,7,8,9-HxCDF	657	657
2,3,4,6,7,8-HxCDF	135	135
1,2,3,4,6,7,8-HpCDF	1,689	1,813
1,2,3,4,7,8,9-HpCDF	104	112
OCDF	624	624
Total 2,3,7,8-CDD	4,396	4,396
Total 2,3,7,8-CDF	4,574	4,725
Total I-TEQ_{DF}	501	508
Total TEQ_{DF}-WHO_{98}	543	550
Total TCDD	554	554
Total PeCDD	860	860
Total HxCDD	2,224	2,224
Total HpCDD	3,180	3,180
Total OCDD	2,331	2,331
Total TCDF	4,335	4,335
Total PeCDF	2,563	2,563
Total HxCDF	4,306	4,306
Total HpCDF	2,030	2,154
Total OCDF	624	624
Total CDD/CDF	23,007	23,131

ng/body = nanograms per body

Source: CARB (1990c)

Table 3-20. CDD/CDF Emission Factors for Sewage Sludge Incinerators

Congener	U.S. EPA (1987a) - 3 facilities Mean Emission Factor (ng/kg)		Green et al. (1995) - 11 facilities Mean Emission Factor (ng/kg)	
	Nondetects Set to Zero	Nondetects Set to 1/2 Det. Limit	Nondetects Set to Zero	Nondetects Set to 1/2 Det. Limit
2,3,7,8-TCDD	0.39	0.44	0.12	0.23
1,2,3,7,8-PeCDD	NR	NR	0.23	0.32
1,2,3,4,7,8-HxCDD	NR	NR	0.03	0.11
1,2,3,6,7,8-HxCDD	NR	NR	0.10	0.16
1,2,3,7,8,9-HxCDD	NR	NR	0.29	0.36
1,2,3,4,6,7,8-HpCDD	NR	NR	2.55	2.70
OCDD	46.2	46.2	13.60	14.00
2,3,7,8-TCDF	179	179	26.60	26.63
1,2,3,7,8-PeCDF	NR	NR	1.98	2.08
2,3,4,7,8-PeCDF	NR	NR	6.84	6.89
1,2,3,4,7,8-HxCDF	NR	NR	2.17	2.24
1,2,3,6,7,8-HxCDF	NR	NR	0.79	0.83
1,2,3,7,8,9-HxCDF	NR	NR	0.03	0.08
2,3,4,6,7,8-HxCDF	NR	NR	1.26	1.46
1,2,3,4,6,7,8-HpCDF	NR	NR	1.46	1.64
1,2,3,4,7,8,9-HpCDF	NR	NR	0.17	0.27
OCDF	109	109	1.22	1.62
Total TCDD	37.6	37.7	35.80	37.81
Total PeCDD	2.66	2.81	0.82	1.63
Total HxCDD	16.6	16.9	1.74	2.25
Total HpCDD	53.9	54.0	4.39	5.03
Total OCDD	46.2	46.2	13.60	14.00
Total TCDF	528	528	123.85	124.10
Total PeCDF	253	253	59.94	60.16
Total HxCDF	75.4	75.9	12.69	13.50
Total HpCDF	144	144	2.63	3.12
Total OCDF	109	109	1.22	1.62
Total I-TEQ_{DF}	NR	NR	6.94	7.19
Total TEQ_{DF}-WHO_{98}	NR	NR	7.04	7.33
Total CDD/CDF	1,266	1,268	257	263

ng/kg = nanograms per kilogram
NR = not reported
Sources: U.S. EPA (1987a); Green et al. (1995)

Table 3-21. CDD/CDF Air Emission Factors for Tire Combustion

Congener/Congener Group	Mean Facility Emission Factor	
	Assuming ND = zero (ng/kg)	Assuming ND = 1/2 det limit (ng/kg)
2,3,7,8-TCDD	0.149	0.149
1,2,3,7,8-PeCDD	0.006	0.026
1,2,3,4,7,8-HxCDD	0.018	0.023
1,2,3,6,7,8-HxCDD	0.055	0.062
1,2,3,7,8,9-HxCDD	0.036	0.048
1,2,3,4,6,7,8-HpCDD	0.379	0.379
OCDD	4.156	4.156
2,3,7,8-TCDF	0.319	0.319
1,2,3,7,8-PeCDF	0.114	0.118
2,3,4,7,8-PeCDF	0.086	0.091
1,2,3,4,7,8-HxCDF	0.103	0.111
1,2,3,6,7,8-HxCDF	0.059	0.090
1,2,3,7,8,9-HxCDF	0.036	0.068
2,3,4,6,7,8-HxCDF	0.100	0.148
1,2,3,4,6,7,8-HpCDF	0.000	0.166
1,2,3,4,7,8,9-HpCDF	0.027	0.095
OCDF	0.756	0.756
Total 2,3,7,8-CDD	4.799	4.843
Total 2,3,7,8-CDF	1.600	1.962
Total I-TEQ_{DF}	0.282	0.311
Total TEQ_{DF}-WHO_{98}	0.281	0.318
Total TCDD	0.153	0.153
Total PeCDD	0.032	0.032
Total HxCDD	0.391	0.391
Total HpCDD	0.695	0.695
Total OCDD	4.156	4.156
Total TCDF	1.204	1.204
Total PeCDF	0.737	0.737
Total HxCDF	0.710	0.710
Total HpCDF	0.119	0.186
Total OCDF	0.802	0.802
Total CDD/CDF	8.999	9.067

ng/kg = nanograms per kilogram
ND = not detected

Source: CARB (1991a)

Table 3-22. CDD/CDF Emission Factors for Combustion of Bleached-Kraft Mill Sludge in Wood Residue Boilers

Congener	Mean Emission Factors (ng/kg feed)	
	Nondetects Set to Zero	Nondetects Set to 1/2 Det. Limit
2,3,7,8-TCDD	0.005	0.013
1,2,3,7,8-PeCDD	0.005	0.012
1,2,3,4,7,8-HxCDD	0.012	0.022
1,2,3,6,7,8-HxCDD	0.050	0.056
1,2,3,7,8,9-HxCDD	0.035	0.043
1,2,3,4,6,7,8-HpCDD	0.301	0.302
OCDD	1.189	1.192
2,3,7,8-TCDF	0.104	0.107
1,2,3,7,8-PeCDF	0.022	0.029
2,3,4,7,8-PeCDF	0.019	0.027
1,2,3,4,7,8-HxCDF	0.069	0.071
1,2,3,6,7,8-HxCDF	0.043	0.046
1,2,3,7,8,9-HxCDF	0.036	0.041
2,3,4,6,7,8-HxCDF	0.004	0.012
1,2,3,4,6,7,8-HpCDF	0.274	0.275
1,2,3,4,7,8,9-HpCDF	0.081	0.083
OCDF	0.187	0.188
Total TCDD	0.101	0.108
Total PeCDD	0.030	0.109
Total HxCDD	0.599	0.600
Total HpCDD	0.956	0.958
Total OCDD	1.189	1.192
Total TCDF	0.560	0.560
Total PeCDF	0.469	0.470
Total HxCDF	0.748	0.748
Total HpCDF	1.102	1.102
Total OCDF	0.187	0.188
Total I-TEQ_{DF}	0.061	0.082
Total TEQ_{DF}-WHO_{98}	0.062	0.087
Total CDD/CDF	5.941	6.037

ng/kg = nanograms per kilogram

Source: NCASI (1995)

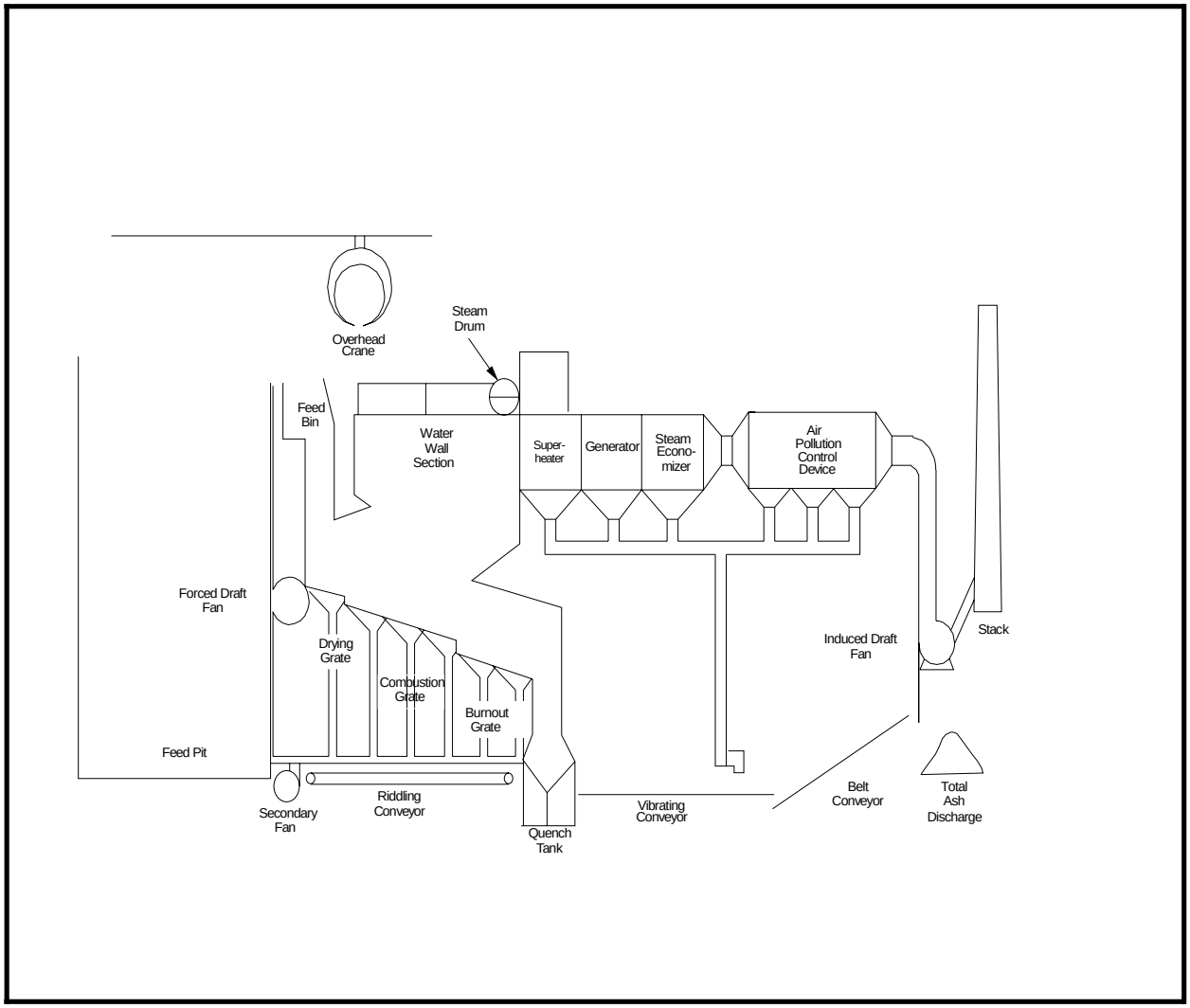


Figure 3-1. Typical Mass Burn Waterwall Municipal Solid Waste Incinerator

Source: U.S. EPA (1997b)

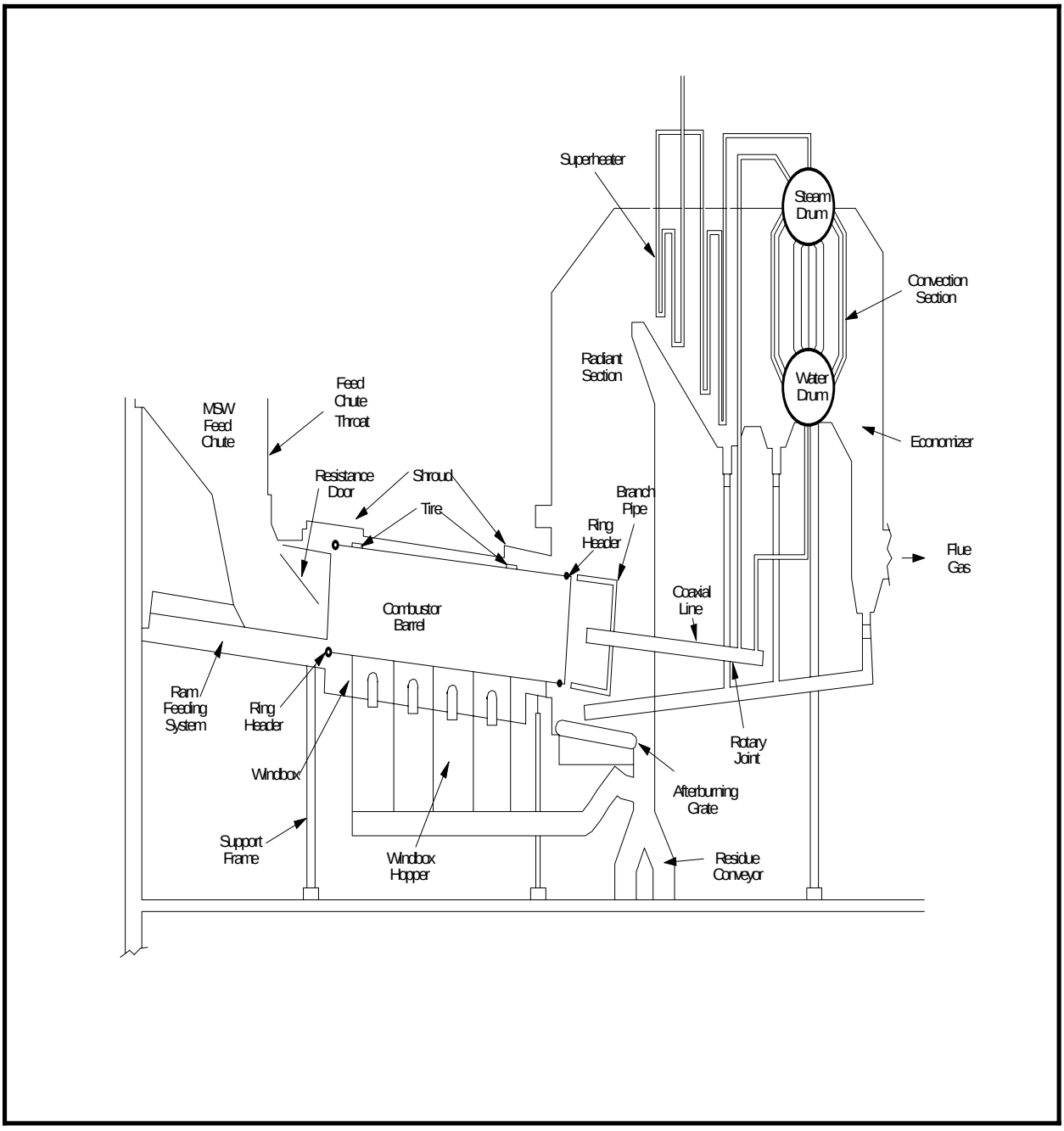


Figure 3-2. Typical Mass Burn Rotary Kiln Combustor

Source: U.S. EPA (1997b)

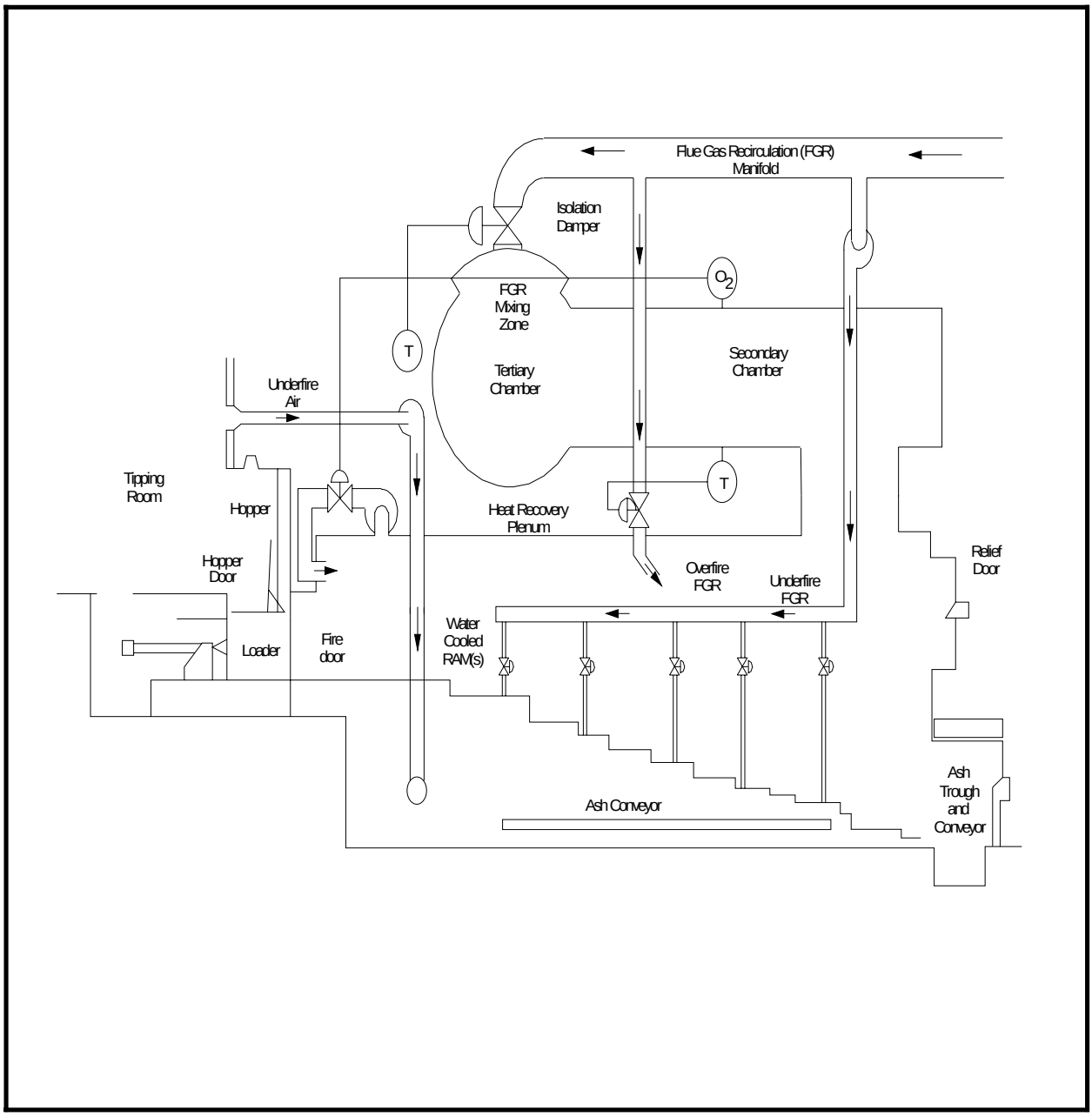


Figure 3-3. Typical Modular Excess-Air Combustor

Source: U.S. EPA (1997b)

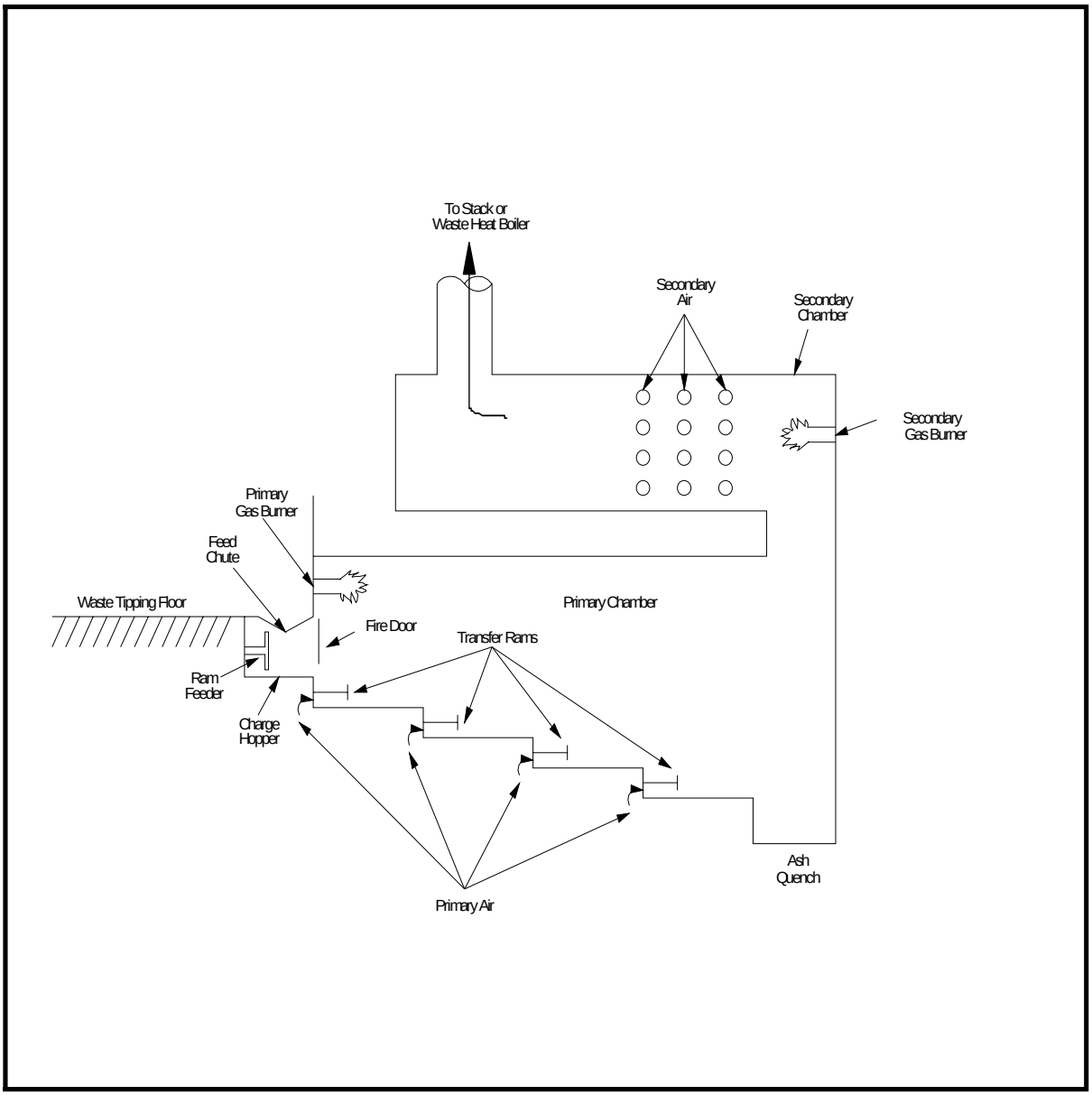


Figure 3-4. Typical Modular Starved-Air Combustor with Transfer Rams

Source: U.S. EPA (1997b)

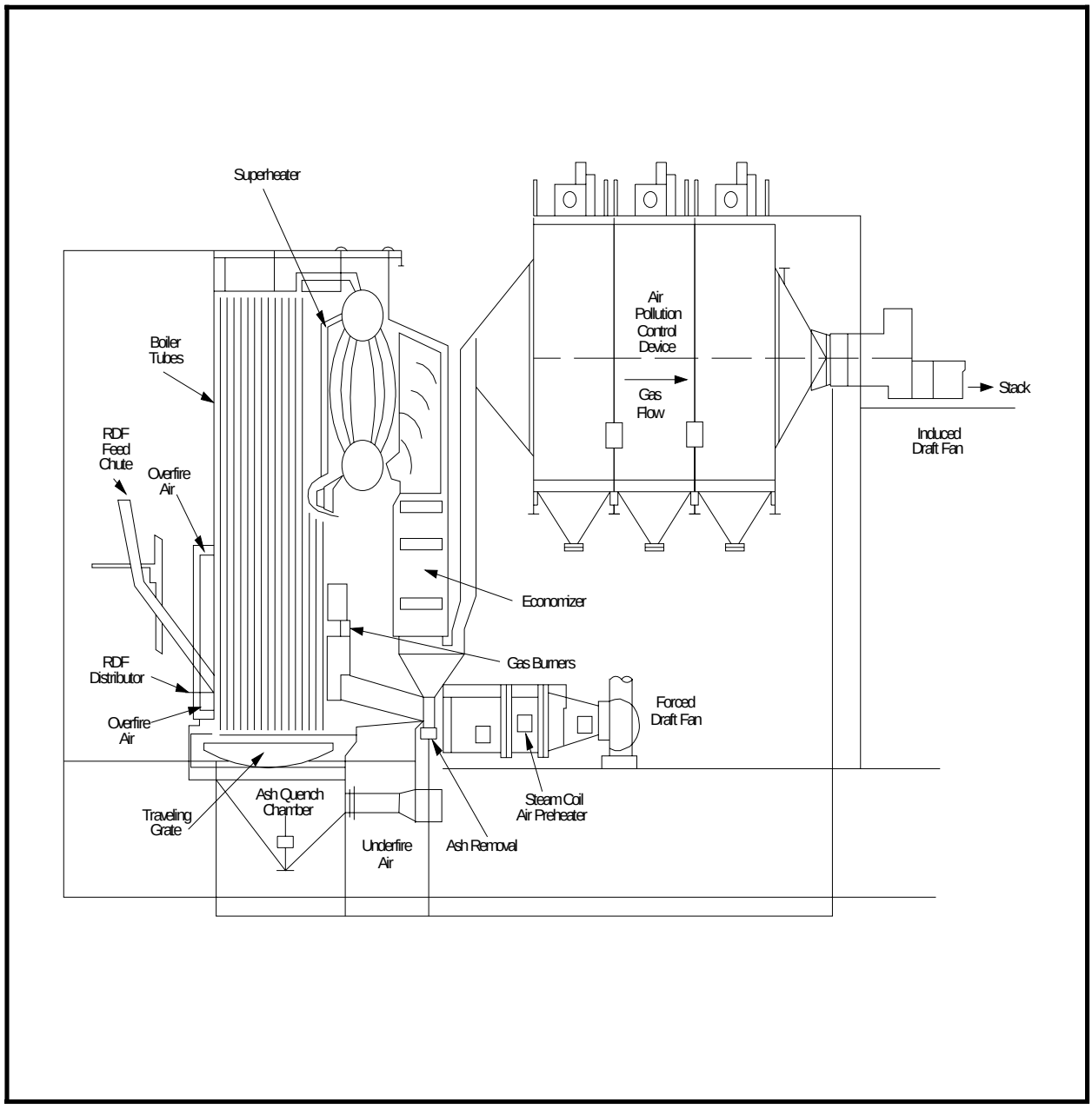


Figure 3-5. Typical Dedicated RDF-Fired Spreader Stoker Boiler

Source: U.S. EPA (1997b)

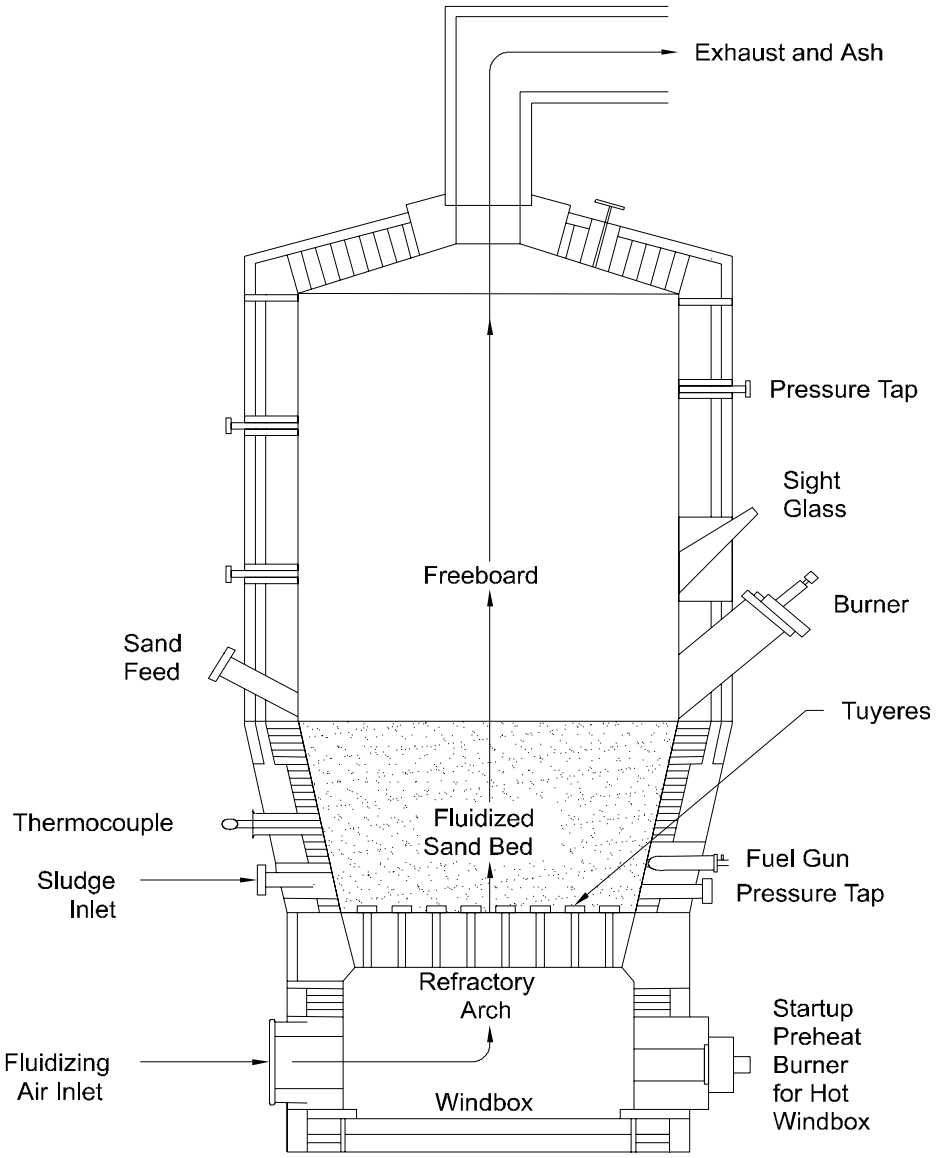
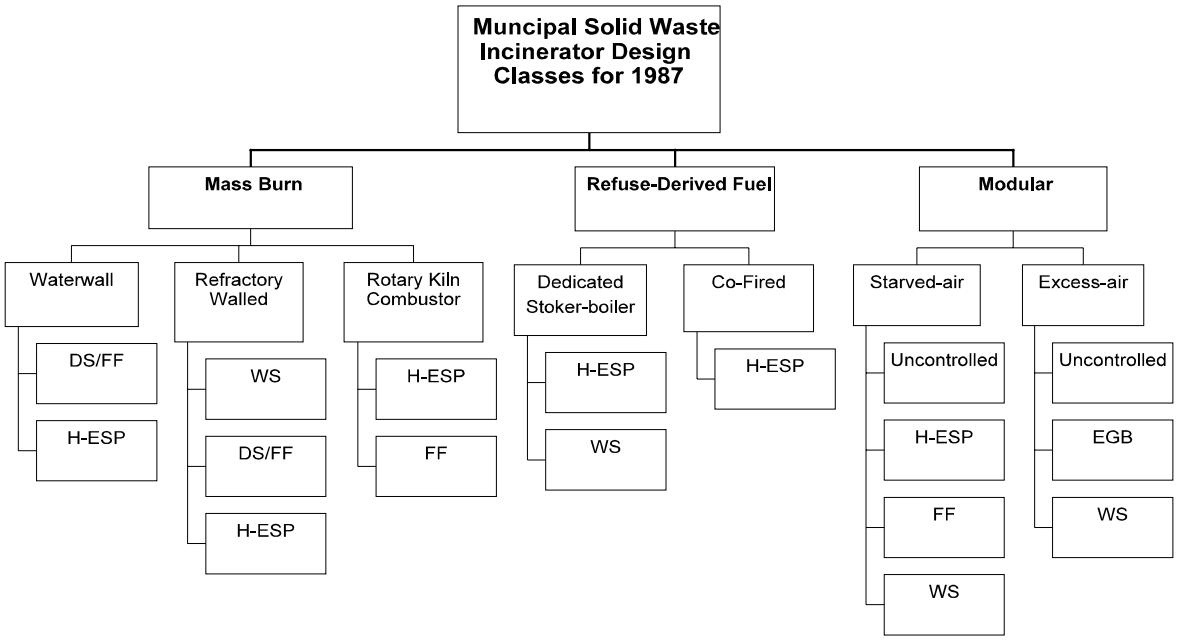


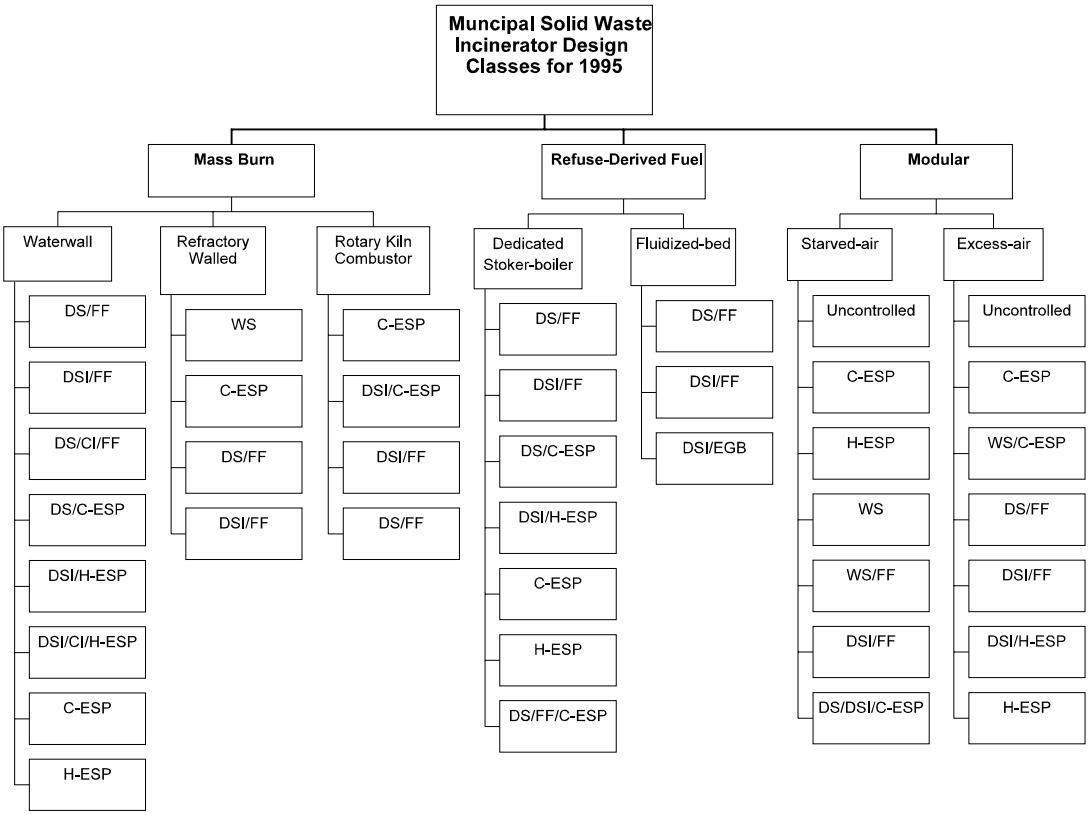
Figure 3-6. Fluidized-Bed RDF Incinerator

Source: U.S. EPA (1997b)



Key: DS/FF = Dry Scrubber combined with a Fabric Filter
H-ESP = Hot-side Electrostatic Precipitator (Temperature at control device is ≥230°C)
WS = Wet Scrubber
UNC = Uncontrolled (no APCD)
EGB = Electro Granular Activated Carbon Bed
FF = Fabric Filter

Figure 3-7. MSWI Design Classes for 1987



Key: DS/FF = Dry Scrubber combined with a Fabric Filter
DSI/FF = Dry Sorbent Injection coupled with a Fabric Filter
DS/CI/FF = Dry Scrubber -Carbon Injection-Fabric Filter
C-ESP = Cold-side Electrostatic Precipitator (Temperature at control device is below $\leq$230°C)
H-ESP = Hot-side Electrostatic Precipitator (Temperature at control device is $\geq$230°C)
WS = Wet Scrubber
UNC = Uncontrolled (no APCD)
EGB = Electro Granular Activated Carbon Bed

Figure 3-8. MSWI Design Classes for 1995

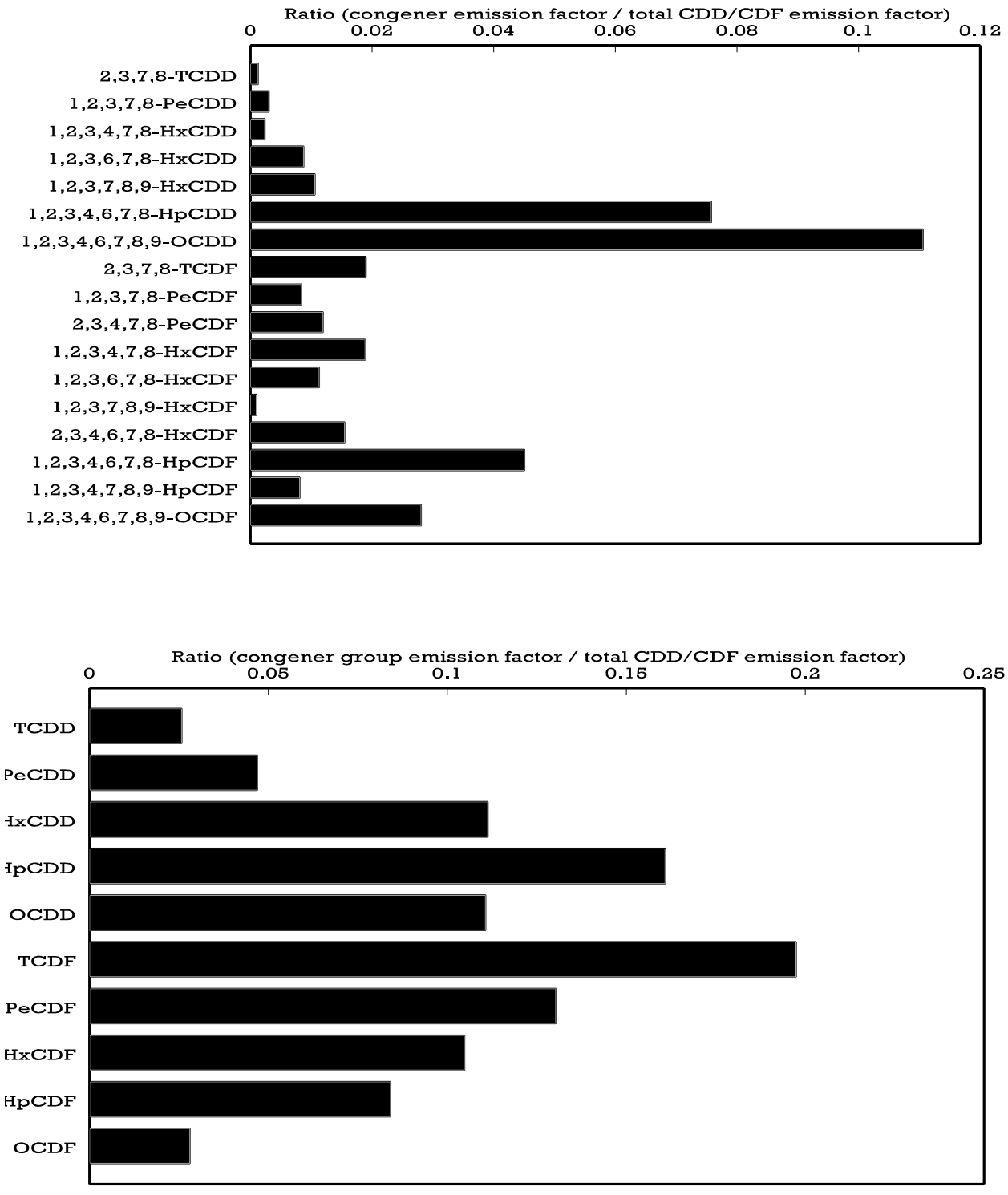


Figure 3-9. Congener and Congener Group Profiles for Air Emissions from a Mass-Burn Waterwall MSWI, Equipped with a Dry Scrubber and Fabric Filter

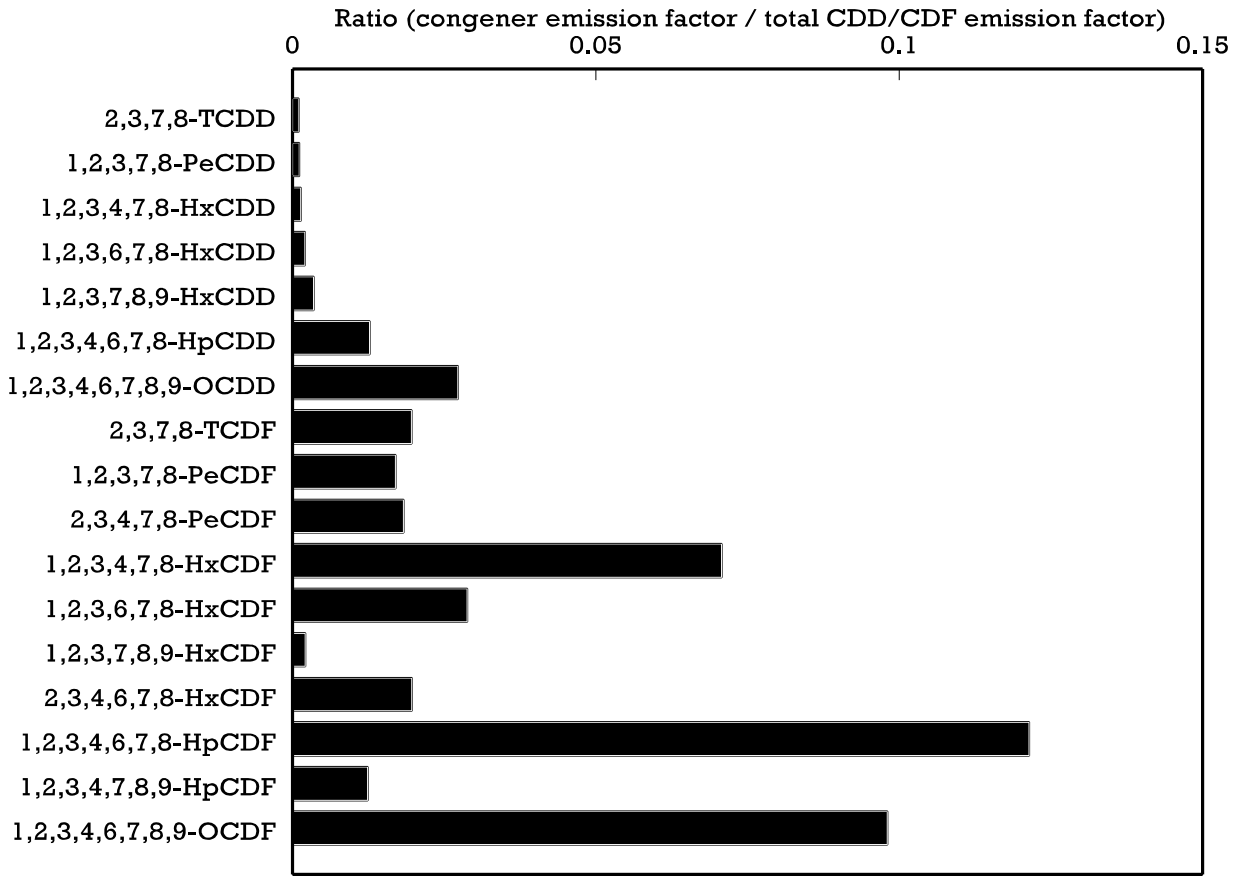


Figure 3-10. Congener Profile for Air Emissions from Hazardous Waste Incinerators

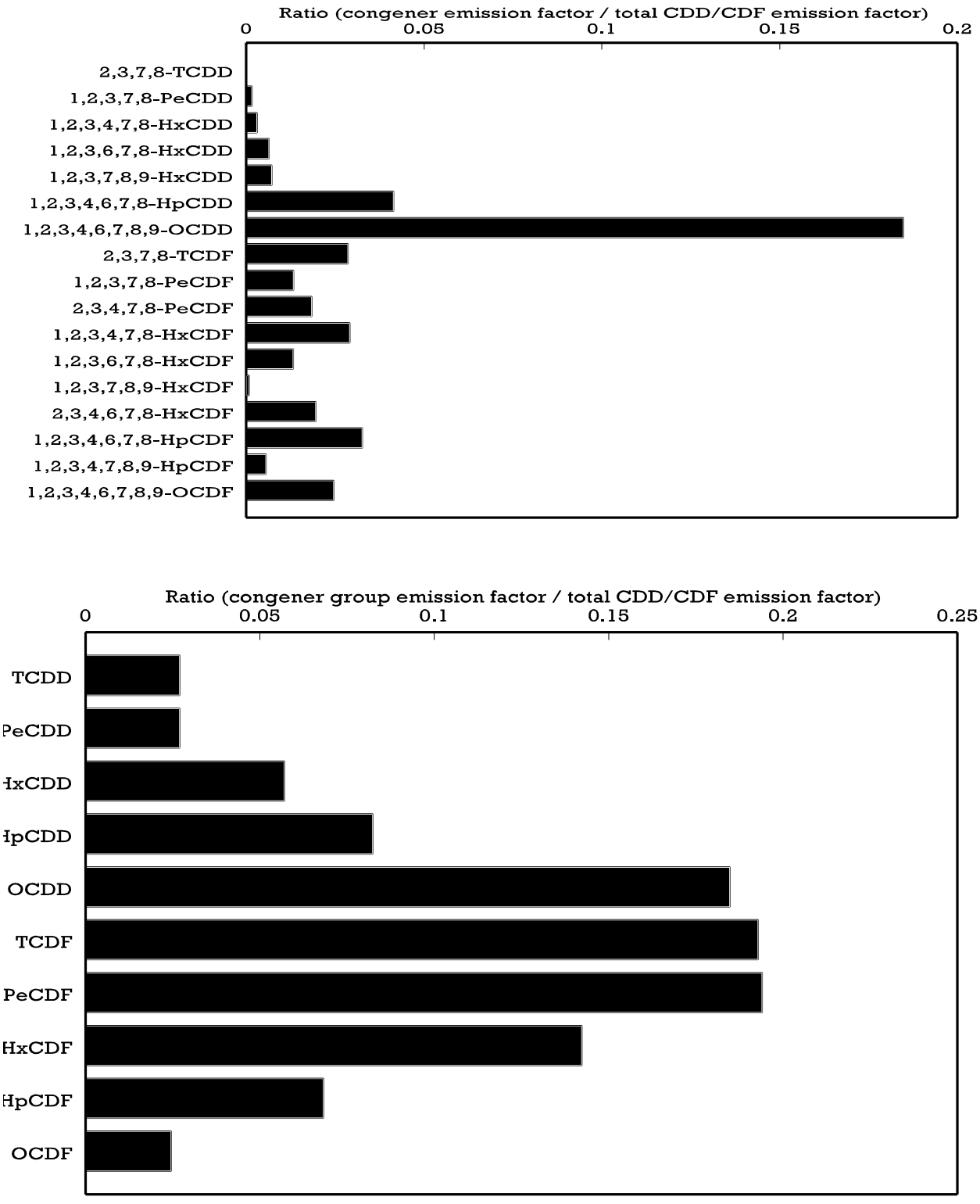


Figure 3-11. Congener and Congener Group Profiles for Air Emissions from Boilers and Industrial Furnaces Burning Hazardous Waste

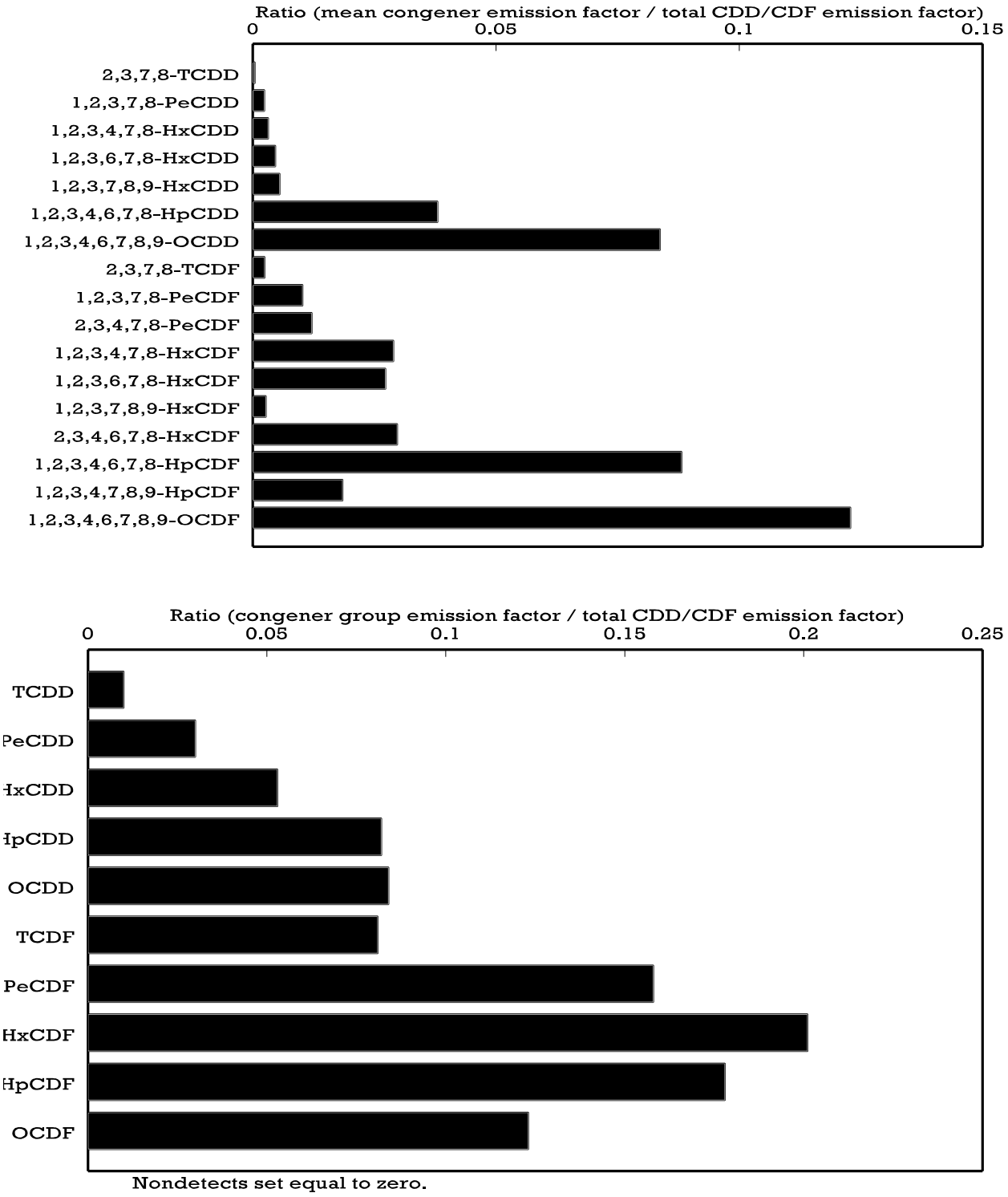


Figure 3-12. Congener and Congener Group Profiles for Air Emissions from Medical Waste Incinerators without APCD

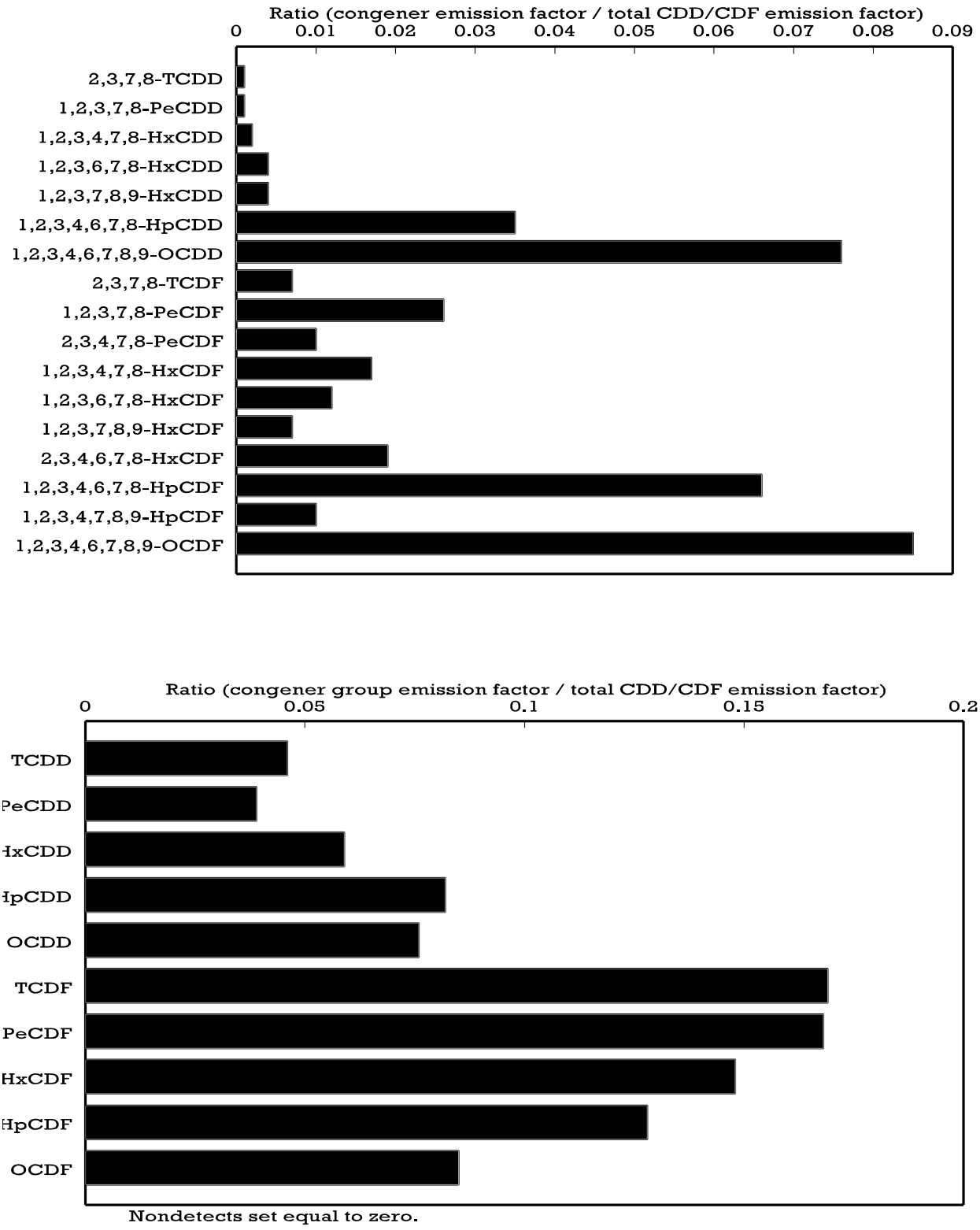
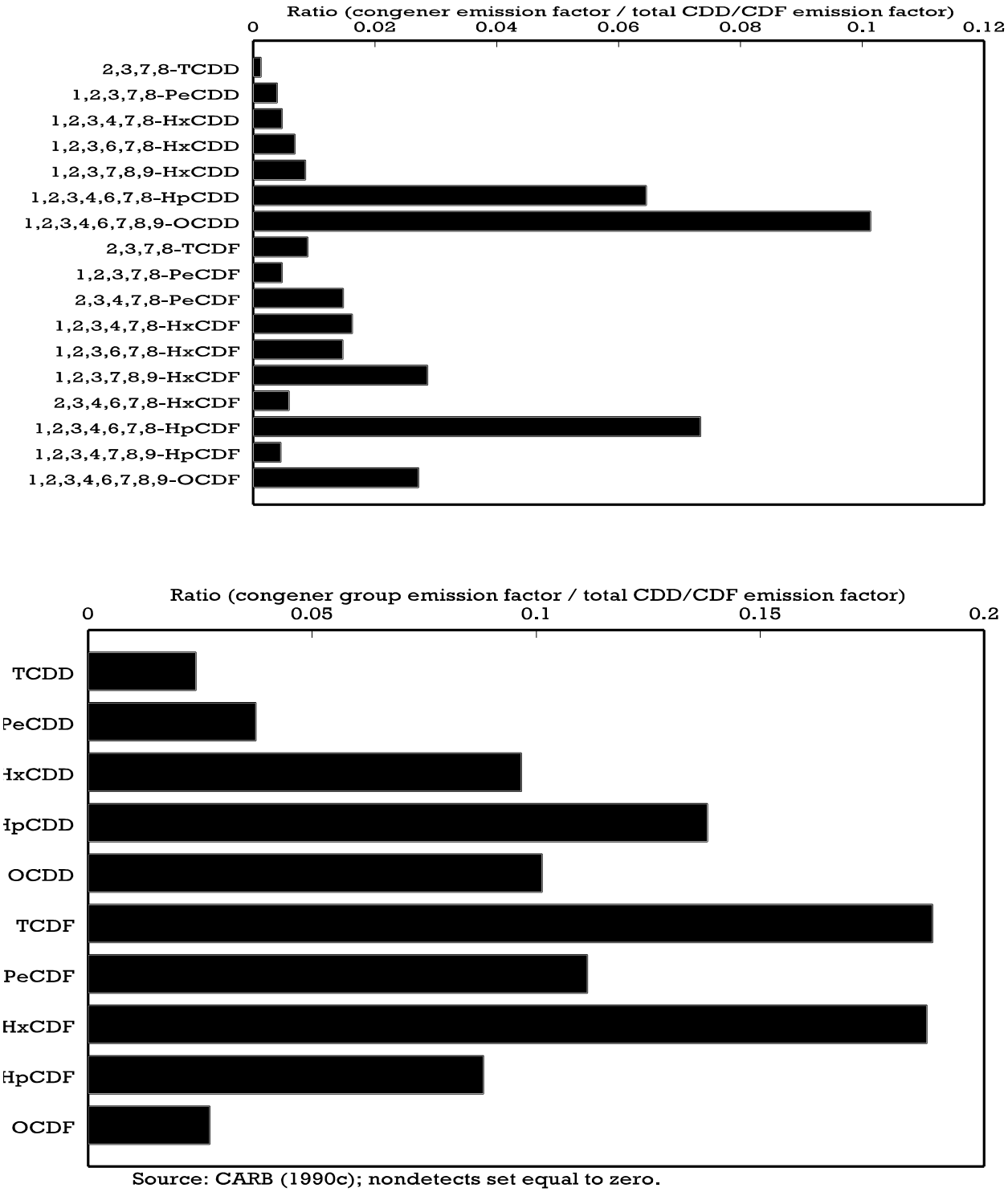


Figure 3-13. Congener and Congener Group Profiles for Air Emissions from Medical Waste Incinerators Equipped with a Wet Scrubber, Baghouse, and Fabric Filter



Source: CARB (1990c); nondetects set equal to zero.

Figure 3-14. Congener and Congener Group Profiles for Air Emissions from a Crematorium

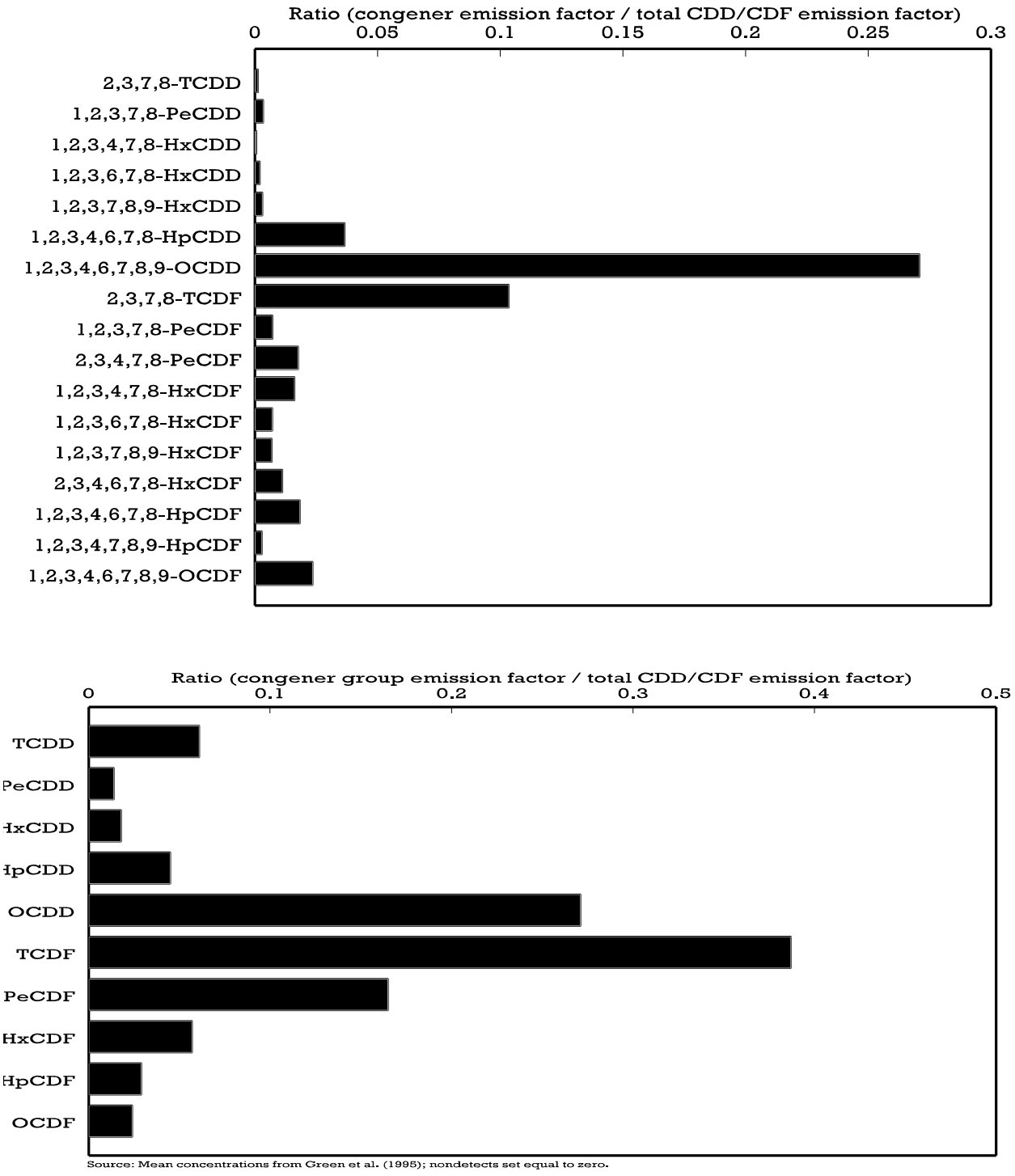
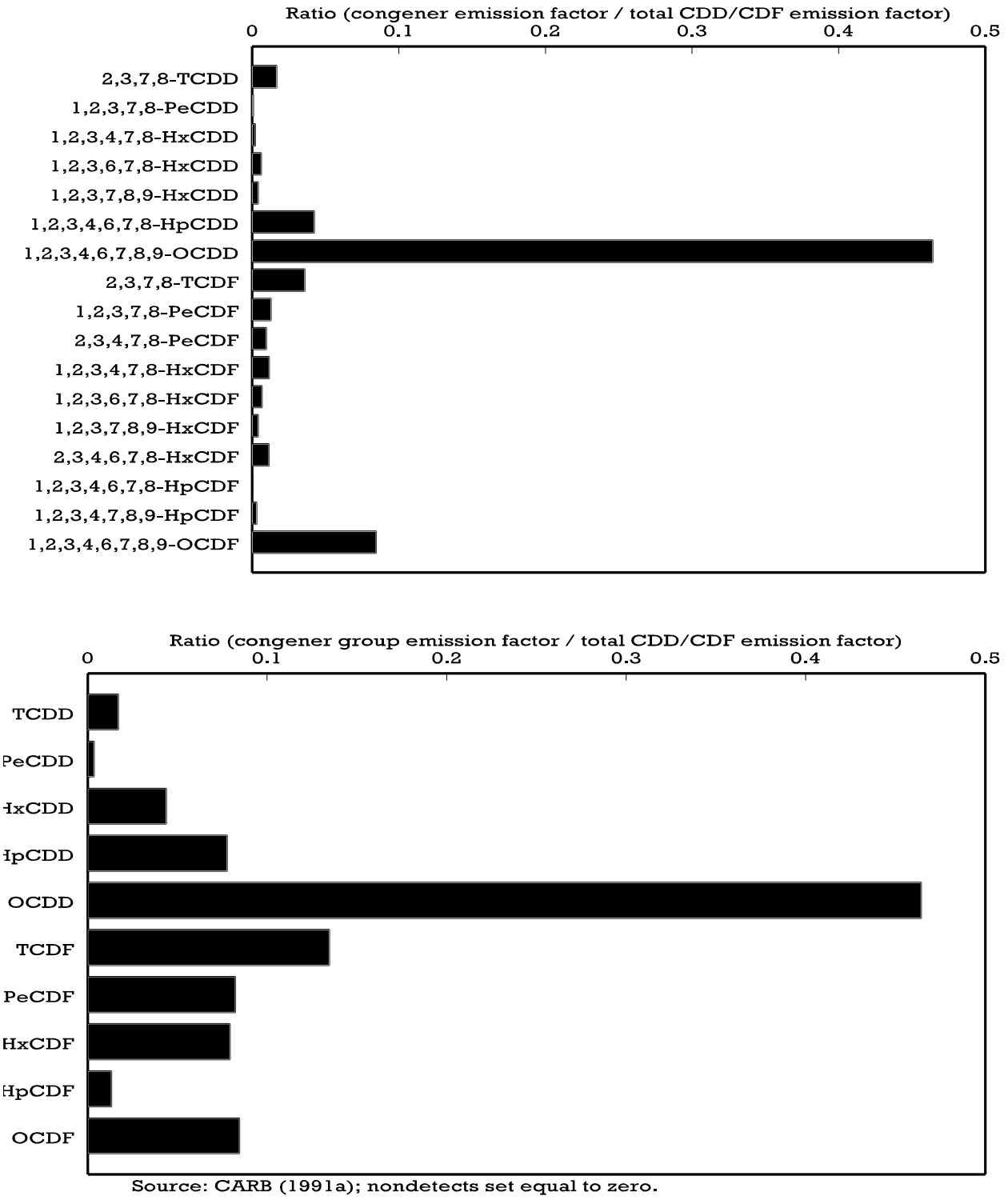


Figure 3-15. Congener and Congener Group Profiles for Air Emissions from Sewage Sludge Incinerators



Source: CARB (1991a); nondetects set equal to zero.

Figure 3-16. Congener and Congener Group Profiles for Air Emissions from a Tire Combustor