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Waste-to-Energy Combustion

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Charles O. Velzy

Private Consultant

Leonard M. Grillo

Grillo Engineering Company

24.1 Introduction

One of the most serious issues facing urbanized areas today is development of cost-effective environmentally acceptable disposal of the community's solid waste. The solid waste generated in a community may be collected by private companies or governmental entities, or portions by both, but the assurance that the waste is ultimately disposed of in an environmentally safe manner is a governmental responsibility.

Solid waste management is a major issue in the United States, because of increasing concerns with environmental problems. One potential solution is to use municipal solid waste, which, for all practical purposes is a renewable commodity, for the generation of electricity. An analysis by Penner and Richards⁵⁴ showed that incineration of municipal waste, even after 30% of the waste was recycled, could provide as much electric power as eight large nuclear or coal generating stations. Their analysis further

concluded that this could provide 1%–2% of the total electric energy needs in the United States at prices competitive with coal-fired base load power plants.

The basic technology for modern waste-to-energy combustion was developed in Europe during the 1960s and 1970s. This technology, which has been modified and improved since its development, has been widely implemented in the United States. However, despite the fact that incineration of solid waste can decrease its volume ninefold and ameliorate the final waste disposal into landfills, the full potential of utilizing solid waste for energy production is not being realized because of widespread fears regarding environmental pollution. In preparing this chapter, the realities of the situation have been taken into account and the discussion emphasizes the prevention of pollution as much or more than the production of power from waste. Waste-to-energy combustion in modern facilities with adequate environmental safeguards and careful monitoring has been shown to be a safe and cost-effective technology that is likely to increase in importance during the next decade.

Two conditions usually point to the use of combustion processes in treating municipal solid waste prior to ultimate disposal: the waste is collected in an urbanized area with little or no conveniently located land for siting of sanitary landfills (need for volume reduction); and markets exist for energy recovered from the combustion process, and possibly for reclaimed materials, with the energy attractively priced. Even some rural areas are currently considering waste to energy facilities.

Modern waste-to-energy (WTE) plants reflect significant advances that have been made in addressing the technical and practical difficulties of material handling, combustion control, and flue gas cleanup. In the early days of waste incineration, when air pollution regulations were undemanding or nonexistent, relatively simple, fixed-grate plants operating on a single- or two-shift basis were common. However, with increasingly stringent air pollution control regulations, more complex plants requiring continuous operation are now being built.

24.2 Waste Quantities and Characteristics

Municipal solid waste (MSW) as used herein refers to solid waste collected from residences and commercial, light industrial and institutional waste. It does not include heavy industrial waste, which is another problem and varies widely in quantity and characteristics, depending on the industry and specific industrial plant. Changes in packaging practices and improvements in the general standard of living have resulted in significant increases in the quantities of solid waste generated over the past 50 years. Additionally, increasing emphasis on and participation in the recycling of wastes by local communities has resulted in significant variations in quantity and characteristics of MSW at the local community level. All of these factors must be considered when planning a WTE facility. [Section 19.3](#) gives more information on waste availability.

24.2.1 Waste Quantities

In the United States approximately 120 million tons of MSW were generated in 1970, increasing to 220 million tons in 1998²⁵ MSW generation is projected to increase to almost 260 million tons by the year 2010.²⁷ At the local level the quantity of solid waste generated varies geographically, daily, and seasonally, according to the effectiveness of the local recycling initiatives, and differences in socioeconomic conditions.⁶⁰

Over the past 40 years, numerous studies by EPA,²³ APWA,² and others⁶⁷ have indicated that urbanized areas in this country generate approximately 2.0 pounds per capita per day of MSW from residences and another 2.0 pounds per capita per day from commercial and institutional facilities, on a national average basis. Thus, a typical community of 100,000 inhabitants would generate about 200 tons per day of gross MSW discards averaged over a 1-year time period.

These projections are subject to adjustments related to specific community characteristics. Thus, communities in the south, with longer active growing seasons than those in the north, tend to produce and collect more yard waste. Recent requirements for on-site disposal and/or composting of yard waste is

changing this variable. Rural communities tend to produce less waste per capita than highly urbanized areas because of their greater potential for on-site waste disposal. In the past, the communities in the north tended to produce more waste in the winter due to the prevalence of heating of homes with solid fuels, which produced large quantities of ashes for disposal. Variations in yard wastes and ashes produced from home heating with solid fuels are also examples of variations in MSW quantities related to seasonal effects. Seasonal variations in MSW generation have been noted to range $\pm 15\%$ from the average, while daily variations in waste collections may range up to $\pm 50\%$ from the average, depending largely on number of collections per week. Daily variations in waste quantities are more important in designing certain plant components, while geographic and seasonal effects are more important in establishing plant size.

Waste quantities are also affected by the effectiveness of local recycling initiatives and by socio-economic conditions. EPA studies have indicated an increase, nationally, in waste recycling from 6.6% in 1960–1970, to 16.2% in 1990,²⁴ and 28.2% in 1998.²⁶ The national recycling rate is projected to increase to about 34% by the year 2010,²⁷ at which time it is expected to level off. A community in New England⁹ projected a 14.0% drop in MSW generation between 1989 and 1991 due to recycling activities in the community, and a 6.0% drop due to the recession during this period in this region of the country. A 15% drop in MSW collections was noted in a Long Island community during a recessionary period in 1972. The impact of recycling on MSW generation should be considered in plant sizing, while the impact of recessionary periods on plant economics may require specific consideration during project planning.

24.2.2 Waste Characteristics

It is important in approaching the design of a WTE facility that one consider the potential variations in both physical and chemical composition of MSW. Historically, one of the most troublesome areas in WTE plants has been materials handling systems. To successfully select materials handling system components and design an integrated process, one must have adequate information on the variability and extremes of the physical size and shape the solid waste facility must handle, the bulk density and angle of repose of the material, and the variation in noncombustible content. This information generally is not available from published surveys and reports, and can only be secured through inspection of the MSW in the field. Materials handling equipment for refuse feeding and residue handling must be large enough and oriented properly to pass the largest bulky items in the MSW, and large enough and rugged enough to handle the quantities of materials required to meet plant design capacity, or the plant will experience expensive periods of down time and might have to be derated.

In the design of the furnace/boiler portion of WTE facilities, the refuse characteristics of interest are the calorific value, moisture content, proportion of noncombustibles, and other components (such as heavy metals, chlorine, and sulfur) whose presence during combustion will result in the need for flue gas cleanup. The capacity of a WTE furnace boiler is roughly inversely proportional to the calorific or heating value of the waste. [Table 24.1](#) illustrates the variation in waste characteristics that has been observed in studies defining the average solid waste composition in the United States over the past 40 years.

As indicated in [Table 24.1](#), approximately 35%–40% of the combustible fraction of MSW is composed of cellulosic material such as paper and wood. This percentage has remained relatively constant over the past 20 years, even after taking into account the greater than fourfold increase in recycling percentage achieved over this period. The remainder of the combustible content is composed of various types of plastics, rubber, and leather. The heat released by burning cellulose is approximately 8000 Btu/lb (on a dry basis), while that released by plastics, rubber, and leather is significantly higher on a per pound, dry basis. Heat released by burning garbage (on a dry basis) is only slightly less than cellulose. However, the moisture content of garbage has been observed to range from 50 to 75%, by weight, while that of the cellulosic fraction of MSW usually ranges from 15 to 30%.

In recent years, it has been observed that the higher heating value (HHV) of the combustible portion of MSW (moisture and ash free) averages about 9400 Btu/lb. Considering the recent changes in MSW composition following recycling (increase in plastics while cellulosic material has remained relatively constant), this moisture and ash free HHV has probably increased to 9500 Btu/lb. Taking 9500 Btu/lb as

TABLE 24.1 Waste Characteristics (in percent)

	Oceanside N Y. 1966–1967	1970 ^a		1998		2010 ^a	
		Generated	After Recovery	Generated	After Recovery	Generated	After Recovery
Paper materials	32.72–53.33	36.6	33.2	38.2	31.1	36.9	27.1
Plastics	2.45–8.82	2.4	2.6	10.2	13.4	12.0	16.7
Rubber & leather	—	2.5	2.4	3.1	3.8	2.8	3.4
Textiles	2.24–3.97	1.7	1.7	3.9	4.7	4.5	5.6
Wood	1.22–6.58	3.1	3.3	5.4	7.1	5.3	7.1
Food (garbage)	7.23–16.70	10.6	11.3	10.0	13.6	11.3	16.2
Yard wastes ^b	0.26–33.33	19.2	20.5	12.6	9.6	11.5	7.0
Noncombustible	22.47–14.36	24.1	24.9	16.6	16.7	15.7	17.0
Total	—	100.0	100.0	100.0	100.0	100.0	100.0
Total weight (in mil. tons)	—	121.0	113.0	220.2	158.1	260.0	171.6
Recovery (recycling & composting)	—	6.6		28.2		34.0	

Note: See indicated references for further details.

^a Details may not add to totals due to rounding

^b Including grass, dirt and leaves

Source: From Marjorie A. Franklin. 2002. [Chapter 5](#), Solid Waste Stream Characteristics in Handbook of Solid Waste Management, 2nd Ed., McGraw Hill; Marjorie A. Franklin. Sept. 2004 personal communication; Kaiser, E. R., Zeit, C. D., and McCaffery, J. B. 1968. Municipal Incinerator Refuse and Residue. Proceedings 1968 National Incinerator Conference, pp. 142–153, ASME, New York.

TABLE 24.2 Variation in Heat Content of MSW

Noncombustible %	15		25	
	Comb. %	Heat Cont. Btu/lb	Comb. %	Heat Cont. Btu/lb
Moisture %				
20	65	6125	55	5225
30	55	5225	45	4275
40	45	4275	35	3325
50	35	3225	25	2375

the moisture and ash free heat content of MSW, Table 24.2 illustrates the variation in as-received heat content that one could expect in MSW with moisture content ranging from 20 to 50% by weight and noncombustible content ranging from 25% by weight (earliest period) to approximately 15% by weight (currently).

Moisture content is a highly important and also a highly variable characteristic of waste materials. The moisture content of MSW is generally around 25%, but has been observed to vary from 15 to 70%. This variation may be due, for example, to seasonal variations in precipitation, the nature of the waste (e.g., grass clippings vs. paper) and the method of storage and collection (e.g., open vs. closed containers/trucks). Thus, after a heavy rain, the moisture content of the solid waste may be so high that it may be difficult to sustain combustion. The combustion of solid waste usually can proceed without supplementary fuel when the heat value is greater than 3500–4000 Btu/lb (8140–9300 kJ/kg). This type of variation in MSW composition must be considered in the design of WTE facilities.

The ultimate or elemental analysis of the combustible portion of the MSW refers to the chemical analysis of the waste for carbon, hydrogen, oxygen, sulfur, chlorine, and nitrogen. This information is used to estimate the heat content of waste, moisture, and ash free; to predict the composition of the flue gases; and, from the last three elements (sulfur, chlorine, and nitrogen), to assess the possible impact of waste combustion on air pollution. A typical analysis of solid waste is presented in Table 24.3.

TABLE 24.3 Analysis of Solid Waste

	Percent by Weight	
	West Europe	U.S.
Proximate analysis		
Combustible	42.1	50.3
Water	31.0	25.2
Ash and inert material	26.9	24.5
Total	100	100
Ultimate (elemental) analysis of combustibles		
Carbon	51.1	50.9
Hydrogen	7.1	6.8
Oxygen	40.1	40.3
Nitrogen	1.2	1.0
Sulfur	0.5	0.4
Chlorine	—	0.6
Total	100	100

Gross heat value, as fired = 3870 Btu/lb (9000 kJ/kg).

Source: From Domalski, E. S., Ledford A. E., Jr., Bruce, S. S., and Churney, K. L. The Chlorine Content of Municipal Solid Waste from Baltimore County, Maryland, and Brooklyn, NY, *Proceedings 1986 National Waste Processing Conference*, Denver, CO, June 1–4, pp. 435–448, ASME, New York; Seeker, W. R., Lanier, W. S., and Heap, M. P. 1987. *Municipal Waste Combustion Study: Combustion Control of Organic Emissions EPA Research Triangle Park, NC*; Suess, M. J., et al. 1985. *Solid Waste Management Selected Topics 1985 WHO Regional Office for Europe, Copenhagen, Denmark*.

24.3 Design of WTE Facilities

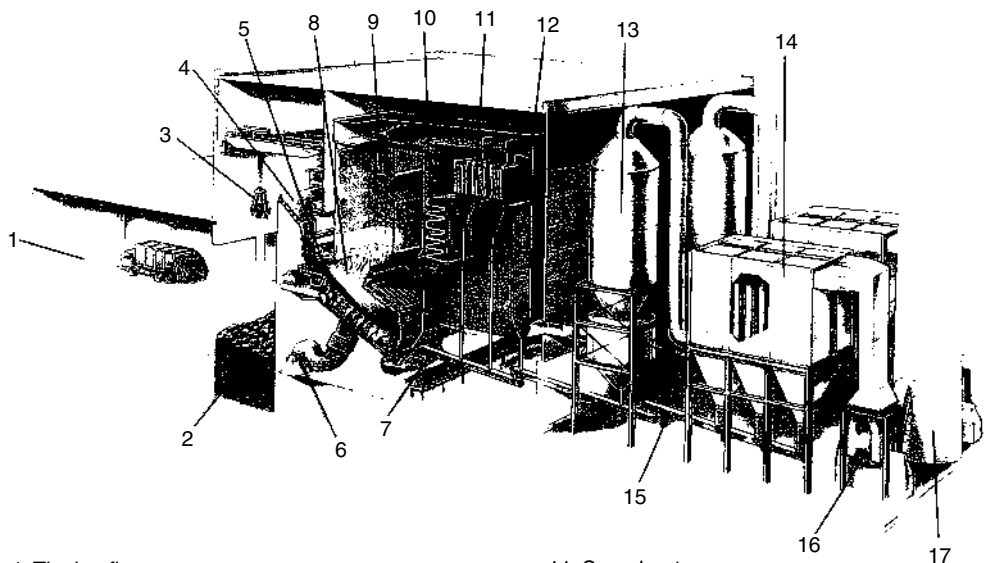
The primary function of a WTE facility is to reduce solid waste to an inert residue with minimum adverse impact on the environment. Thermal efficiency, in terms of maximizing the capture of energy liberated in the combustion process, is of secondary importance. WTE facilities are usually classified as mass-burn systems, or refuse-derived fuel (RDF) systems.

24.3.1 General Features

24.3.1.1 Types of Facilities

Mass-burn systems are large facilities (usually over 200 tons per day) that burn, as-received, unprocessed MSW which is extremely heterogeneous. Most mass-burn systems burn the waste in a single combustion chamber under conditions of excess air (i.e., more than is needed to complete combustion) (see Figure 24.1). The waste is burned on a sloping, moving grate, which helps agitate the MSW and mixes it with combustion air. Many different proprietary grate systems exist.

In refuse-derived fuel (RDF) systems, usually large facilities, the MSW is first processed (see Figure 24.2) by mechanical means to produce a more homogeneous material prior to introduction into a furnace/boiler. Several types of RDF can be made—coarse, fluff, powder, and densified. These differ in complexity and horsepower requirements of the waste processing facilities, size of particle produced, and whether or not the material is compacted under pressure into pellets, briquettes, or similar forms. The coarse type of RDF is the most common form produced at this time.



- | | |
|--|--|
| 1. Tipping floor | 11. Superheater |
| 2. Refuse holding pit | 12. Economizer |
| 3. Feed crane | 13. Dry gas scrubber |
| 4. Feed chute | 14. Baghouse or electrostatic precipitator |
| 5. Martin stoker grate | 15. Fly ash handling system |
| 6. Combustion air fan | 16. Induced draft fan |
| 7. Martin residue discharger and handling system | 17. Stack |
| 8. Combustion chamber | |
| 9. Radiant zone (furnace) | |
| 10. Convection zone | |

FIGURE 24.1 A typical Covanta facility.

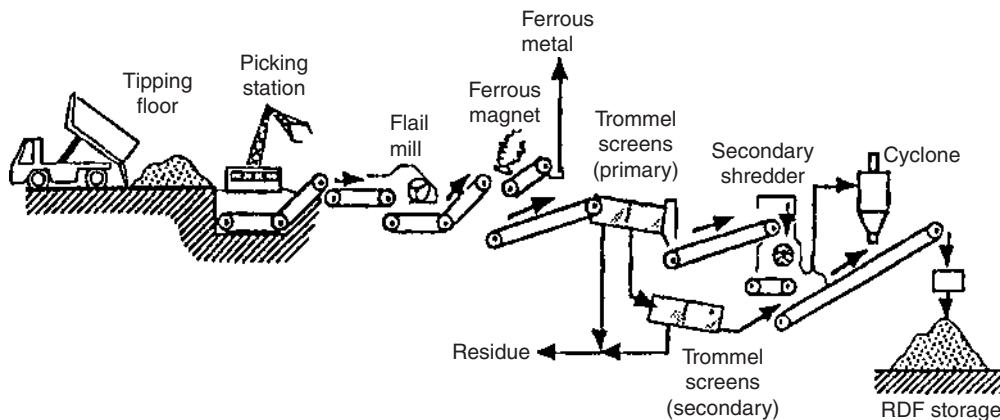


FIGURE 24.2 RDF processing system.

RDF can be burned in one of the two types of boilers. It can be used as the sole or primary fuel in dedicated boilers (see Figure 24.3) or it can be co-fired with conventional fossil fuels in existing industrial or utility boilers. One advantage of these systems is that RDF can be produced at one location for use at a nearby off-site boiler, allowing for flexibility in locating processing facilities. Also, some materials, such as steel and glass, can be recovered for recycling during the initial processing step.

Mass-burn and RDF systems together account for 86 of the 98 currently operating waste-to-energy facilities and 98% of the waste combustion capacity. Modular units, described briefly later, account for the other 12 units and 2% of the waste combustion capacity.⁴²

24.3.1.2 Operation and Capacity

The capacity to be provided in a facility is a function of the area and population to be served; and the rate of refuse production for the population served. A small plant (100 tons per day) without energy recovery might not be operated on weekends. For capacities above 400 tons per day, or any plant with energy recovery, economic and/or equipment operating considerations usually dictate three-shift operation, seven days per week.

If collection records, preferably by weight, are available for the community, forecasts for determining required plant capacity can be made with reasonable accuracy. If records are not available, refuse quantities for establishing plant size may be approximated by assuming a refuse generation rate of 4.0 pounds per capita per day when there is little or no waste from industry. Of course, in planning for plant capacity, the impact of local recycling activities on both quantity and characteristics of MSW must be considered as discussed earlier.

Other factors must be taken into account in establishing the size or capacity of a facility. Should the facility serve only one community, or should it be regional and serve several communities? What are the possible benefits of economies of scale? What is the impact of the cost of hauling refuse to a central point on overall project economics? There is substantial evidence available at present to show that implementation becomes much more difficult as the number of separate political jurisdictions is increased. Imposition of regional plans on local jurisdictions to achieve economies of scale, where it cannot be conclusively demonstrated that such regional plans make sound economic sense based on the total cost of the solid waste management plan, including the cost of transporting the solid waste to the regional facility, is, at best, unwise. Economies of scale in these projects have tended to be illusory, while haul costs to gather sufficient waste together to achieve the economies of scale have tended to be ignored in developing total project economics.

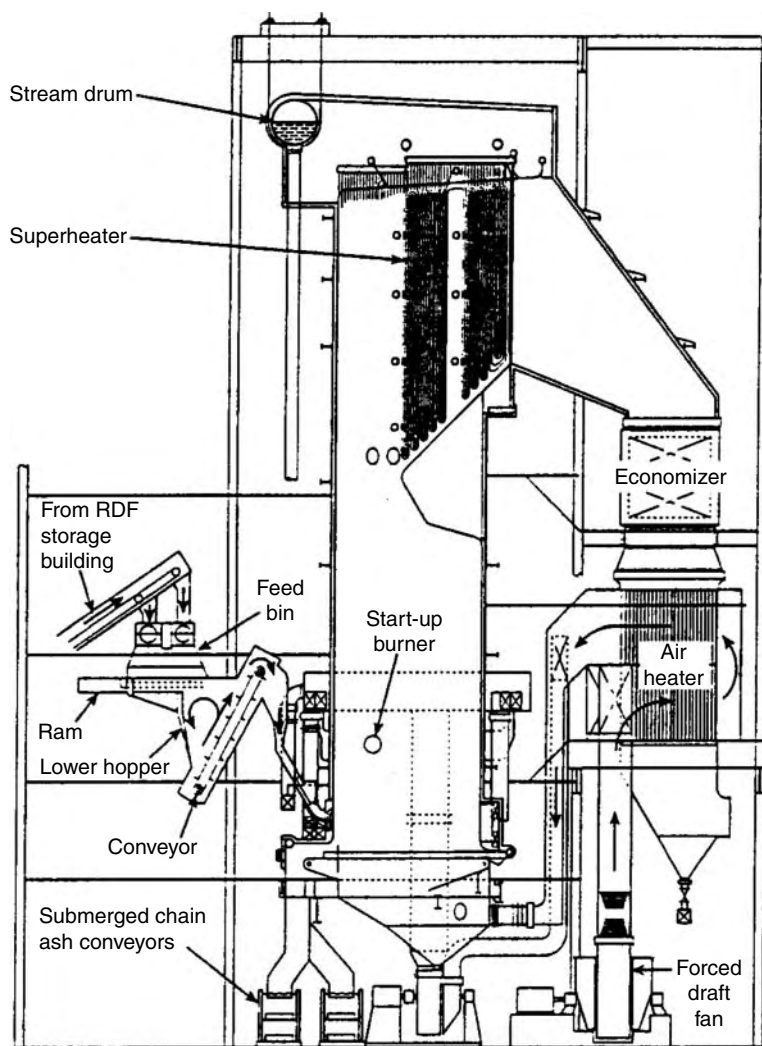


FIGURE 24.3 West Palm Beach, FL, RDF-fired boiler by the Babcock and Wilcox Company.

24.3.1.3 Siting

One of the key issues to face in implementing a WTE project is locating a site for the facility. Since MSW is usually delivered to these plants by truck, inevitably there will be substantial truck traffic in the vicinity of the plants. The equipment and processes used in these plants are industrial in nature. They are generally noisy at the source and tend to produce dust and odors. These facts indicate that it is desirable to site such plants in industrial or commercial areas.⁴⁶ It has been contended, as cited in a 1989 OTA report⁶⁸ “that sites are sometimes selected to avoid middle- and higher-income neighborhoods that have sufficient resources to fight such development.”

Plants should be located near major highways to minimize the impact from increased truck traffic. As shown by operating WTE plants in Europe and the United States, it is possible to control all nuisance conditions by proper attention to the details of plant design. The local impact of truck deliveries to the plant can be minimized by providing sufficient length of access road so that refuse truck queuing does not take place on public highways. Odors and noise can be confined to the plant building. Odors and fugitive dust can be destroyed by collecting plant air and using it for combustion air supply. Noise should be

attenuated at the source to maintain healthful working conditions. In all cases, there is no need to adversely impact the surrounding neighborhood. Proper attention to architectural treatment can result in a structure that blends into its surroundings; if sited in industrial or commercially zoned areas.

Since considerable vertical distance is frequently required in the passage of MSW through a mass-burn WTE plant, there is an advantage in a sloping or hillside site. Collection trucks can deliver MSW at the higher elevation, while residue trucks operate at the lower elevation, requiring minimum site regrading. This consideration does not generally apply to RDF plants.

24.3.2 Fuel Handling

24.3.2.1 Refuse Receipt, Processing, and Storage

Scales, preferably integrated into an automated record keeping system, should be provided to record the weight of MSW delivered to the WTE plant. Either the entire tipping area or individual tipping positions should be enclosed so as to control potential nuisance conditions in the vicinity of the plant, such as blowing papers, dust, and/or odors. The number of tipping positions provided should take into consideration the peak number of trucks expected per hour at the facility and should be located so the trucks have adequate time and room to maneuver to and from the dumping positions while minimizing queue time.

Collections usually are limited to one 8-hour daily shift 5 days per week (sometimes with partial weekend collection) while burning will usually be continuous, so ample storage must be provided. This usually requires 2–3 days of refuse storage at most WTE plants. Seasonal and cyclic variations should also be a consideration in establishing plant storage requirements.

Refuse storage in large mass-burn plants is normally in long, relatively narrow, and deep pits extending along the front of the furnaces. It will generally be necessary to rehandle the refuse dumped from the trucks. In some mass-burn plants and in RDF plants, floor dumping and storage of the MSW either on the dump floor or in shallow, relatively wide pits is common practice.

When computing the dimensions required for storage of as-received MSW, the required volume may be determined based on an MSW bulk density of from 400 to 600 lb/yd³ (240–360 kg/m³).^{2,61} Other factors to consider in sizing and laying out refuse storage facilities in WTE plants is that refuse flows very poorly and can maintain an angle of repose greater than 90°. Thus, MSW is commonly stacked in storage facilities to maximize storage capacity.

Sizing a refuse storage pit requires the use of empirical data, judgment, site constraints, and knowledge of plant layout and operations. The pit should be at least long enough to provide sufficient truck tipping positions so that the trucks are not unduly delayed in discharging their waste (tipping) into the pit. It has been found in practice that it takes an average of 10 min for the truck to perform the tipping operation. This time may be shorter for packer trucks and longer for transfer vehicles. Each tipping position must provide at least 14 ft. of unobstructed width for this operation. Ideally, 20 ft. should be allowed for each tipping position to allow for convenient truck access and space for armored building support columns.

The pit should be capable of holding a minimum of 3 days' storage at the facility's maximum continuous rating. The desired volume should be based on a bulk density of about 500 lb/cy of waste. The dimensions of the pit will be dependent on site constraints and the facility design. The pit is usually at least as long as the width of all the boilers it feeds. The depth will be dependent on groundwater conditions, but should be 30–45 ft. deep if possible. The total volume of storage should equal the volume in the pit up to the tipping floor level plus the volume above the tipping floor assuming the waste is stacked at a 45° from the charging floor wall to the tipping floor. The remainder of the pit will be used for the grapple to move waste away from the tipping positions. After the waste has been stacked, the grapple can remove the material against the tipping floor wall and form a trench, since the waste will maintain a vertical face when stacked.

At most newer and more successful RDF plants, after receiving the MSW in a floor dump type of operation, the MSW is loaded onto conveyors that carry the material to flail mills or trommels with

bag-breaking blades. These facilities break apart the bags containing the waste, allowing glass and some metals to be separated from the remaining MSW. The separated MSW, primarily the light combustible fraction, is then reduced in size. Removal of the glass prior to the size reduction process alleviates the problem, experienced in earlier plants, of contamination of combustible material with glass shards.

Processes to produce powdered fuel or RDF fuel pellets, although interesting, have not been developed to a state of commercial availability. A process to produce RDF by “hydro-pulping” after being attempted in two full-scale plants, was not commercially successful.

24.3.2.2 Refuse Feeding

Batch feeding of MSW, practiced in the past in mass-burn plants, is undesirable and is not practiced in modern plants. In the larger mass-burn plants, the solid waste is usually moved from the storage pit to a charging hopper by a traveling bridge crane and an orange-peel type of grapple. The grapple size is established by a duty cycle analysis, taking into account the quantity of material that must be moved from the pit to the furnaces, the distances over which the material must be moved, allowable crane speeds, and the need to rehandle (mixing and/or stacking) material in the pit. Grapples can range in size from 1.5 to 8 yd³ (1–6 m³) capacity and larger.

The crane used in this service should be capable of meeting the severest of duty requirements.⁵³ The load lifting capability is established by adding to the grapple weight, 1.5 times the volumetric capacity of the grapple times a density of MSW of 600–800 lb/yd³ (360–480 kg/m³).⁴⁰ In the past, the crane has been operated from an air-conditioned cab mounted on the bridge. However, crane operation is now centralized in a fixed control room, usually located at the charging floor elevation and either over the tipping positions opposite the charging hoppers or in the vicinity of the charging hoppers.

In modern mass-burn plants, the MSW is deposited from the crane grapple into a charging hopper. The charging hopper, which is built large enough to prevent spillage on the charging floor and with slopes steep enough to prevent bridging, is placed on top of a vertical feed chute that discharges the MSW into the furnace. The feed chute may be constructed of water cooled steel plates or steel plates lined with smooth refractory material. The chute is normally at least 4 ft. (1.2 m) wide, to pass large objects with a minimum of bridging, and the width of the furnace. It is kept full of refuse to prevent uncontrolled admission of air into the furnace. The refuse is fed from the bottom of the feed chute into the furnace by a portion of the mechanical grate, or by a ram. The ram generally provides better control of the rate of feed into the furnace than the older technique of using a portion of the mechanical grate for refuse feed.

In RDF plants, conveyors, live bottom bins, and pneumatic handling of the size-reduced MSW combustible material have been utilized. The fuel material is usually blown into these furnaces, where it is partially burned while in suspension, with combustion being completed on grates at the bottom of the furnace. These fuel feeding systems are generally more complex than the mass-burn systems.

24.3.3 Combustion Principles

Combustion is the rapid oxidation of combustible substances with release of heat. Oxygen is the sole supporter of combustion. Carbon and hydrogen are by far the most important of the combustible substances. These two elements occur either in a free or combined state in all fuels—solid, liquid, and gaseous. Sulfur is the only other element considered to be combustible. In combustion of MSW, sulfur is a minor constituent with regard to heating value. However, it is a concern in design of the air pollution control equipment. The only source of oxygen considered here will be the oxygen in the air around us.

Table 24.4 displays the elements and compounds that play a part in the combustion process. The elemental and molecular weights displayed are approximate values which are sufficient for combustion calculations. Nitrogen is listed as chemical nitrogen N₂, with a molecular weight of 28.0 and as atmospheric nitrogen, N_{2atm}, which is a calculated figure to account for trace constituents of dry air. Water occurs as a vapor in air and in the products of combustion and as a liquid or vapor constituent of MSW fuel.

TABLE 24.4 Elements and Compounds Encountered in Combustion

Substance	Molecular Symbol	Molecular Weight	Form	Density (lb/ft. ³)
Carbon	C	12.0	Solid	—
Hydrogen	H ₂	2.0	Gas	0.0053
Sulfur	S	32.1	Solid	—
Carbon monoxide	CO	28.0	Gas	0.0780
Oxygen	O ₂	32.0	Gas	0.0846
Nitrogen	N ₂	28.0	Gas	0.0744
Nitrogen atmos.	N _{2atm}	28.2	Gas	0.0748
Dry air		29.0	Gas	0.0766
Carbon dioxide	CO ₂	44.0	Gas	0.1170
Water	H ₂ O	18.0	Gas/liquid	0.0476
Sulfur dioxide	SO ₂	64.1	Gas	0.1733
Oxides of nitrogen	NO _x	—	Gas	—
Hydrogen chloride	HCl	36.5	Gas	0.1016

Source: From Hecklinger, R. S. 1996. *The Engineering Handbook*, CRC Press, Inc., Boca Raton, FL.

A U.S. standard atmosphere of dry air has been defined as a mechanical mixture of 20.947% O₂, 78.086% N₂, 0.934% Ar (argon), and 0.033% CO₂ by volume.¹⁷ The percentages of argon and carbon dioxide in air can be combined with chemical nitrogen to develop the following compositions of dry air by volume and by weight that can be used for combustion calculations:

Constituent	% by Volume	% by Weight
Oxygen, O ₂	20.95	23.14
Atmospheric nitrogen, N _{2atm}	79.05	76.86

Atmospheric air also contains some water vapor. The level of water vapor in air, or its humidity, is a function of atmospheric conditions. It is measured by wet and dry bulb thermometer readings and a psychrometric chart. If specific data are not known, the American Boiler Manufacturers Association recommends a standard of 0.013 pounds of water per pound of dry air, which corresponds to 60% relative humidity and a dry bulb temperature of 80°F.

Table 24.5 displays the chemical reactions of combustion. These reactions result in complete combustion; that is, the elements and compounds unite with all the oxygen with which they are capable of entering into combination. In actuality, combustion is a more complex process in which heat in the combustion chamber causes intermediate reactions leading up to complete combustion.

TABLE 24.5 Chemical Reactions of Combustion

Combustible	Reaction
Carbon	C + O ₂ = CO ₂
Hydrogen	2H ₂ + O ₂ = 2H ₂ O
Sulfur	S + O ₂ = SO ₂
Carbon monoxide	2CO + O ₂ = 2CO ₂
Nitrogen	N ₂ + O ₂ = 2NO
Nitrogen	N ₂ + 2O ₂ = 2NO ₂
Nitrogen	N ₂ + 3O ₂ = 2NO ₃
Chlorine	4Cl + 2H ₂ O = 4HCl + O ₂

Source: From Hecklinger, R. S. 1996. *The Engineering Handbook*, CRC Press, Inc., Boca Raton, FL.

An example of intermediate steps to complete combustion would be when carbon reacts with oxygen to form carbon monoxide and, later in the combustion process, the carbon monoxide reacts with more oxygen to form carbon dioxide. The combined reaction produces precisely the same result as if an atom of carbon combined with a molecule of oxygen to form a molecule of carbon dioxide in the initial reaction. An effectively controlled combustion process results in well less than 0.01% of the carbon in the fuel leaving the combustion chamber as carbon monoxide; and the remaining 99.99% of the carbon in the fuel leaves the combustion process as carbon dioxide. It should also be noted with regard to Table 24.5 that some of the sulfur in a fuel may combust to SO_3 rather than SO_2 with a markedly higher release of heat. However, it is known that only a small portion of the sulfur will combust to SO_3 and some of the sulfur in fuel may be in the form of pyrites (FeS_2), which do not combust at all. Therefore, only the SO_2 reaction is given. Also, some nitrogen is converted to oxides of nitrogen (NO_x), and some chlorine is converted to hydrogen chloride in the presence of moisture in the flue gas. While these components do not factor into the combustion calculations, they are important for the purpose of establishing air pollution control requirements.

Factors directly affecting furnace design are the moisture and the combustible content of the solid waste to be burnt and the volatility of the material to be burnt. The means for temperature control and sizing of flues and other plant elements should be based on design parameters that result in large sizes. Combustion controls should provide satisfactory operation for loads below the maximum rated capacity of the units.

The combustible portion of MSW is composed largely of cellulose and similar materials originating from wood, mixed with appreciable amounts of plastics and rubber, as well as some fats, oils, and waxes. The heat released by burning dry cellulose is approximately 8000 Btu/lb, while that released by certain plastics, rubber, fats, oils, and so on, may be as high as 17,000 Btu/lb. If MSW consists of five parts cellulose and one part plastics, rubber, oil, and fat, the heat content of the dry combustible matter only is approximately 9500 Btu/lb.

The heat released in combustion of basic combustible substances is displayed in Table 24.6. The heating value of a substance can be expressed either as higher (or gross) heating value or as lower (or net) heating value. The higher heating value takes into account the fact that water vapor formed or evaporated in the process of combustion includes the latent heat of vaporization, which could be recovered if the products of combustion are reduced in temperature sufficiently to condense the water vapor to liquid water. The lower heating value is predicated on the assumption that the latent heat of vaporization will not be recovered from the products of combustion.

The heat released during combustion may be determined in a bomb calorimeter, a device with a metal container (bomb) immersed in a water jacket. A 1 g MSW sample is burned with a known quantity of oxygen, and the heat released is determined by measuring the increase in temperature of the water in the water jacket. Since the bomb calorimeter is cooled to near ambient conditions, the heat recovery measured includes the latent heat of vaporization as the products of combustion are cooled and condensed in the bomb. That is, the bomb calorimeter inherently measures higher heating value (HHV). It has been customary in the United States to express heating value as HHV. In Europe and elsewhere, heating value is frequently expressed as the lower heating value (LHV).

TABLE 24.6 Heat of Combustion

Combustible	Molecular Symbol	Heating Value (Btu per Pound)	
		Gross	Net
Carbon	C	14,100	14,100
Hydrogen	H_2	61,100	51,600
Sulfur	S	3980	3980
Carbon monoxide	CO	4350	4350

Source: From Hecklinger, R. S. 1996. *The Engineering Handbook*, CRC Press, Inc., Boca Raton, FL.

Heating value can be converted from HHV to LHV if weight decimal percentages of moisture and hydrogen (other than the hydrogen in moisture) in the fuel are known, using the following formula:

$$\text{LHV}_{\text{Btu/lb}} = \text{HHV}_{\text{Btu/lb}} - [\% \text{H}_2\text{O} + (9 \times \% \text{H}_2)] \times (1050 \text{ Btu/lb}) \quad (24.1)$$

$$\text{LHV}_{\text{J/kg}} = \text{HHV}_{\text{J/kg}} - [(9 \times \% \text{H}_2) + \% \text{H}_2\text{O}] \times (2240 \text{ KJ/kg}) \quad (24.2)$$

For example (using data from Table 24.9),

$$\text{LHV}_{\text{Btu/lb}} = \text{HHV}_{\text{Btu/lb}} - [\% \text{H}_2\text{O} + (9 \times \% \text{H}_2)] \times 1050 \text{ Btu/lb}$$

$$\text{LHV}_{\text{Btu/lb}} = 4940 - [0.30 + (9 \times 0.047)] \times 1050$$

$$\text{LHV}_{\text{Btu/lb}} = 4940 - [0.30 + 0.42] \times 1050$$

$$\text{LHV}_{\text{Btu/lb}} = 4940 - 756 = 4184 \text{ Btu/lb}$$

Another method for determining the approximate higher heating value for MSW is to perform an ultimate analysis and then apply Dulong's formula:

$$\text{HHV}_{(\text{Btu/lb})} = 14,544 \text{ C} + 62,028 \left(\text{H}_2 - \frac{\text{O}_2}{8} \right) + 4050 \text{ S} \quad (24.3)$$

where C, H₂, O₂, and S represent the decimal proportionate parts by weight of carbon, hydrogen, oxygen, and sulfur in the fuel. The term O₂/8 is a correction used to account for hydrogen which is already combined with oxygen in the form of water. For example (using data from Table 24.9)

$$\text{HHV}_{(\text{Btu/lb})} = 14,544 \text{ C} + 62,028 \left(\text{H}_2 - \frac{\text{O}_2}{8} \right) + 4050 \text{ S}$$

$$\text{HHV} = 14,544 \times 0.257 + 62,028 \left(0.047 - \frac{0.21}{8} \right) + 4050 \times 0.001$$

$$\text{HHV} = 3738 + 62,028(0.047 - 0.026) + 4.0$$

$$\text{HHV} = 3738 + 62,028 \times 0.021 + 4.0$$

$$\text{HHV} = 3738 + 1303 + 4 = 5045 \text{ Btu/lb}$$

An alternate method of estimating the HHV is to multiply the approximate dry combustable HHV of 9,500 Btu/lb by the weight fraction of combustibles:

$$\text{HHV} = 9500 \times (1 - \text{moisture} - \text{ash})$$

$$\text{HHV} = 9500 \times (1 - 0.30 - 0.18)$$

$$\text{HHV} = 9500 \times 0.52 = 4940 \text{ Btu/lb}$$

The American Society for Testing and Materials (ASTM) publishes methods for determining the ultimate analysis of solid fuels such as MSW.³ The ultimate analysis of a fuel is developed through measures of carbon, hydrogen, sulfur, nitrogen, ash, and moisture content. Oxygen is normally determined "by difference"; that is, once the percentages of the other components are measured, the remaining material is assumed to be oxygen. For solid fuels, such as MSW, it is frequently desirable to determine the proximate analysis of the fuel. The procedure for determining the proximate analysis is also prescribed by ASTM.³ The qualities of the fuel measured in percentage by weight are moisture, volatile matter, fixed carbon, and ash. This provides an indication of combustion characteristics of a solid fuel. As a solid fuel is heated to combustion, first the moisture in the fuel evaporates, then some of the combustible constituents volatilize (gasify) and combust as a gas with oxygen, and the remaining combustible constituents remain as fixed carbon in a solid state and combust with oxygen to form carbon dioxide. The material remaining after combustion is complete is the ash. MSW, with a high percentage of volatiles and a low percentage of fixed carbon, burns with much flame.

Table 24.7 displays ignition temperatures for combustible substances in MSW. The ignition temperature is the temperature to which the combustible substance must be raised before it will unite in chemical combination with oxygen. Thus, the temperature must be reached and oxygen must be present for combustion to take place. Ignition temperatures are not fixed temperatures for a given substance. The actual ignition temperature is influenced by combustion chamber configuration, oxygen

TABLE 24.7 Ignition Temperatures

Combustible	Molecular Symbol	Ignition Temperature °F
Carbon (fixed)	C	650
Hydrogen	H ₂	1080
Sulfur	S	470
Carbon monoxide	CO	1170

Source: From Stultz, S. C. and Kitto, J. B. eds. 1992. *Steam: Its Generation and Use*, 40th Ed., The Babcock and Wilcox Co., Barberton, OH.

fuel ratio, and synergistic effect of multiple combustible substances. The ignition temperature of MSW is the ignition temperature of its fixed carbon component. The volatile components of MSW are gasified but not ignited before the ignition temperature is attained.

The oxygen, nitrogen, and air data displayed in Table 24.8 represent the weight of air theoretically required to completely combust one pound of a combustible substance. The weight of oxygen required is the ratio of molecular weight of oxygen to molecular weight of the combustion constituent as displayed in Table 24.5. The weights of nitrogen and air required are calculated from the percentage by weight constituents of dry air. In actuality, to achieve complete combustion, air in excess of the theoretical requirement is required for complete combustion to increase the likelihood that all of the combustible substances are joined with sufficient oxygen to complete combustion. The level of excess air required in the combustion of MSW depends on the configuration of the combustion chamber, the nature of the fuel firing equipment, and the effectiveness of mixing combustion air with the MSW. An excess air level of 80% is commonly associated with combustion of MSW in modern WTE facilities. Excess air is generally monitored using an oxygen analyzer at the economizer outlet. The type of analyzer used at waste-to-energy facilities generally reports percent wet oxygen. The dry oxygen can be estimated by assuming 15% moisture in the flue gas using the following equation:

$$\text{dry oxygen} = (\text{wet oxygen}) / (1 - \text{percent moisture}/100), \text{ or } \text{dry oxygen} = (1.176)(\text{wet oxygen})$$

Excess air can be approximated by the following equation:

$$\text{Excess air} = 55.2 - 10.46 \times (\text{dry O}_2) + 1.4 \times (\text{dry O}_2)^2$$

where dry O₂ is the percentage dry oxygen in the flue gas.

Excess air serves to dilute and thereby reduce the temperature of the products of combustion. The reduction of temperature tends to reduce the heat energy available for useful work. Therefore, the actual excess air used in the combustion process is a balance between the desire to achieve complete combustion and the objective of maximizing the heat energy available for useful work.

TABLE 24.8 Theoretical Combustion Air

Combustible	Pounds Per Pound of Combustible					
	Required for Combustion			Products of Combustion		
	O ₂	N _{atm}	Air	CO ₂	H ₂ O	N _{atm}
Carbon	2.67	8.87	11.54	3.67		8.87
Hydrogen	8.00	26.57	34.57		9.00	26.57
Sulfur	1.00	3.32	4.32	2.00		3.32
Carbon monoxide	0.57	1.89	2.46	1.57		1.89

Source: From Hecklinger, R. S. 1996. *The Engineering Handbook*, CRC Press, Inc., Boca Raton, FL.

TABLE 24.9 Sample Calculation for Municipal Solid Waste (MSW)

Air Calculations (80% Excess Air)				
Ultimate Analysis				
Substance	Fraction % by Weight	Oxygen Required for Combustion, lb/lb of Element	Theoretical Oxygen, lb/lb of Element	Theoretical Dry Air, lb/lb of Element
Carbon	0.279	2.67	0.745 ^a	3.218 ^b
Hydrogen	0.037	8.00	0.296 ^a	1.279 ^b
Oxygen	0.209	—	—	—
Nitrogen	0.005	—	—	—
Sulfur	0.002	1.00	0.002 ^a	0.009 ^b
Ash	0.187			
Fuel moisture	0.281			
Total	1.000		1.043	4.505
Less oxygen in fuel			(0.209)	(0.903) ^c
Air Required at 100% theoretical air			0.834	3.603
180% of theoretical air (80% excess air)			1.501	6.485
Excess HHV = 5100 Btu/lb			0.667	2.882
Products of Combustion				
			lb/lb of Element	lb of Product
Carbon dioxide			3.67	1.024 ^d
Moisture from hydrogen			9.00	0.333 ^d
Oxygen				0.667 ^e
Nitrogen				4.989 ^f
Sulfur dioxide			2.00	0.004 ^d
Moisture from fuel			1.00	0.281 ^d
Moisture from air				0.084 ^g
Total moisture				0.698 ^h
Total				7.382
LHV = 5100 - [0.281 + (9 × 0.037)] × 1050 = 4455 BTU/lb				
Temperature developed in combustion = 60 + 4455 / [(0.698 × 0.55 ⁱ) + (7.382 - 0.698) × 0.28 ^j] = 2035°F				
Check:				
Total products of combustion = 180% of theoretical air + moisture from air + fraction percent by weight of C, H, O, N, S, and moisture				
7.382 = 6.485 + 0.084 + 0.279 + 0.037 + 0.209 + 0.005 + 0.002 + 0.281 = 7.382				

^a Weight percent of element times oxygen required for combustion.

^b Theoretical oxygen times 4.32.

^c Amount of theoretical air due to oxygen in fuel.

^d Weight percent of element times lb/lb of element.

^e Excess oxygen.

^f 180% of theoretical dry air times 0.7686 plus weight percent of nitrogen in fuel.

^g Moisture in combustion air = 0.013 times 180% of theoretical air (0.013 lb moisture per lb of dry air at 80°F and 60% relative humidity).

^h Total of moisture from combustion of hydrogen, moisture in fuel, and moisture from air.

ⁱ Heat capacity of water vapor.

^j Heat capacity of dry flue gas.

It is frequently useful to know the temperature attained by combustion. The heat released during combustion heats the products of combustion to a calculable temperature. It must be understood that the calculation procedure presented here assumes complete combustion and that no heat is lost to the surrounding environment. Thus, it is a temperature that is useful to compare one combustion process with another. The heat available for heating the products of combustion is the lower heating value of the fuel. The increase in temperature is the lower heating value divided by the mean specific heat of the products of combustion. The mean specific heat is a function of the constituent products of combustion ($W_{P.C.}$) and the temperature. To approximate the theoretical temperature attainable, one can use a specific heat of 0.55 Btu/lb per °F for water vapor (W_{H_2O}) and 0.28 Btu/lb per °F for the other gaseous products of combustion ($W_{P.C.} - W_{H_2O}$). Thus, the formula approximating the temperature attained during combustion is

$$T_{\text{comb}} = T + \frac{LHV_{\text{Btu/lb}}}{0.55W_{H_2O} + 0.28(W_{P.C.} - W_{H_2O})} \quad (24.4)$$

For example (using data from Table 24.9)

$$T_{\text{comb}} = T_{\text{ambient}} + \frac{LHV_{\text{Btu/lb}}}{0.55W_{H_2O} + 0.28(W_{P.C.} - W_{H_2O})}$$

If the ambient temperature is assumed to be 60°F, then

$$T_{\text{comb}} = 60 + \frac{4184}{0.55 \times 0.81 + 0.28(7.55 - 0.81)}$$

$$T_{\text{comb}} = 60 + \frac{4184}{0.45 + 1.89} = 60 + \frac{4184}{2.34}$$

$$T_{\text{comb}} = 1848 \cong 1850^\circ F$$

Typical combustion calculations are provided in Table 24.9 for MSW to determine the products of the combustion process. Each of the combustible substances combines and completely combusts with oxygen as displayed in Table 24.5. The weight ratio of oxygen to the combustible substance is the ratio of molecular weights. Table 24.8 displays the weight or volume of oxygen theoretically required for complete combustion of one pound of the combustible substance. Sulfur dioxide from combustion of sulfur in fuel is combined with CO₂ in the sample calculation as a matter of convenience. If desired, a separate column can be prepared for sulfur dioxide in the products of combustion. Oxygen in the fuel combines with the combustible substances in the fuel, thereby reducing the quantity of air required to achieve complete combustion. The sample calculation uses the weight percentages of oxygen to reduce the theoretical air requirements and the nitrogen in the products of combustion. The decimal percentage of excess air is multiplied by the total theoretical air requirement to establish the weight of excess air and the total air requirement including excess air.

24.3.4 Furnaces

While the general principles of a modern waste combustor burning as-received MSW are common to all types, the specific solid waste combustion process is rather complex. The waste is heated by contact with hot combustion gases or preheated air, and by radiation from the furnace walls. Drying occurs in a temperature range of 122°F–302°F (50°C–150°C). At higher temperatures, volatile matter is formed by complicated thermal decomposition reactions. This volatile matter is generally combustible and, after ignition, produces flames. The remaining material is further degased and burns much more slowly. In an RDF furnace (see Figure 24.3), most of the volatile matter and some of the fixed carbon is burned in suspension while the remaining fixed carbon is combusted on a grate at the bottom of the furnace.

The complexity of the combustion of solid waste streams results from the nature of the decomposition and burning reactions and their association with heat transfer, air flow, and diffusion. In most waste combustors, combustion takes place while the solids are supported on and conveyed by a grate. Since the early 1960s, most MSW incinerators have incorporated one of a number of available proprietary grate systems that allow continuous feed of unscreened waste into and movement through furnaces with integral boiler facilities. The grate performs several functions: provides support for the refuse, admits underfire air through openings in the grate surface, transports the solid waste from feed mechanism to ash quench, agitates the bed, and serves to agitate and redistribute the burning mass.

The basic design factors which determine furnace capacity are grate area and furnace volume. Also, the available capacity and method of introducing both underfire and overfire air will influence, to a lesser extent, furnace capacity. Required grate area, in a conservative design, is normally determined by limiting the burning rate to between 60 and 70 lb/ft.² hr (290–340 kg/m² hr) of grate area.² This is based on limiting the heat release rate loading on the grate to 250,000–300,000 Btu/ft.² of grate per hr (2.8–3.4 GJ/m²/hr).

Furnace volume required is established by the rate of heat release from the fuel. Thus, furnace volume is generally established by using heat release rates ranging from 12,500 to 20,000 Btu/ft.³/hr (450–750 MJ/m³/hr), with the lower heat release rate being more desirable from the standpoint of developing a conservative design. A conservative approach to design in this area is desirable because of probable periodic operation above design capacity to meet short-term higher than normal refuse collections and possible receipt of high heat-content waste.

Water wall units burning as-received MSW have been built as small as 75–100 tons per day (68–91 tons/day) capacity. However, the cost per ton of rated capacity of such units is relatively high. A more common unit size for both mass-burn and RDF furnaces is 250–1000 tons/day (225–900 tons/day), while water wall mass-fired units have been built as large as 750–1200 tons/day (675–1090 tons/day) capacity.⁷

The primary objective of a mechanical grate in a mass-burn furnace is to convey the refuse from the point of feed through the burning zone to the point of residue discharge with a proper depth of fuel and sufficient retention time to achieve complete combustion. The refuse bed should be agitated so as to enhance combustion. However, the agitation should not be so pronounced that particulate emissions are unreasonably increased. The rate of movement of the grate or its parts should be adjustable to meet varying conditions or needs in the furnace.

In the United States over the past 20 years, several types of mechanical grates have been used in continuous feed furnaces burning as-received MSW. These include reciprocating grates (see Figure 24.4), rocking grates (see Figure 24.5), roller grates (see Figure 24.6), and water wall rotary combustors for mass-burn units, and traveling grates for RDF units (see Figure 24.3). The reciprocating grates, rocking grates, and roller grates agitate and move the refuse material through the furnace by the movement of the grate elements and the incline of the grate bed. Additional agitation is obtained, particularly in the reciprocating grate, by drops in elevation between grate sections. The rotary combustor slowly rotates to tumble the refuse material, which is conveyed through the inside of the cylinder. The combustor is inclined from the horizontal so that gravity assists in moving the material through the unit. The traveling grate conveys the refuse through the furnace on the grate surface. Stirring is accomplished by building the grate in two or more sections, with a drop between sections to agitate the material.

Other grate systems have been developed in Europe for burning as-received MSW, some of which are currently being utilized in plants being constructed or in operation in the United States. The roller grate, or so-called Dusseldorf System (see Figure 24.6), uses a series of 5 or more rotating cylindrical grates, or drums, placed at a slope of about 30°. The refuse is conveyed by the surface of the drums, which rotate in the direction of refuse flow, and is agitated as it tumbles from drum to drum. Underfire air is introduced through the surface of the drums. Both the Von Roll and the Martin grates use a reciprocating motion to push the refuse material through the furnace. However, in the Martin grate (see Figure 24.7), the grate surface slopes steeply down from the feed end of the furnace to the ash discharge end and the grate sections push the refuse uphill against the flow of waste, causing a gentle tumbling and agitation of the fuel bed.

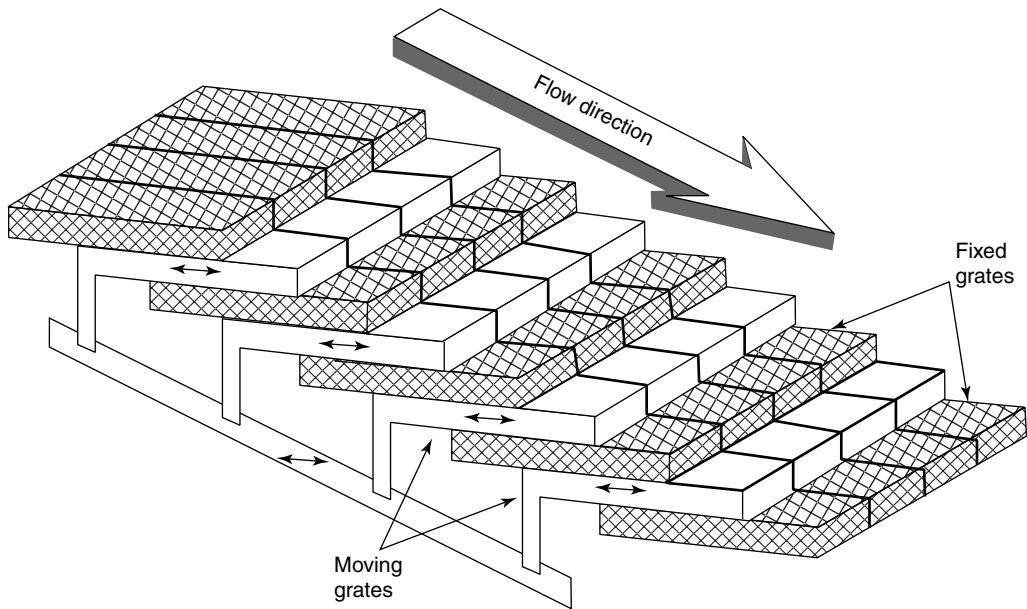


FIGURE 24.4 Reciprocating grates.

Another variable feature in the various grate designs is the percentage of open area to allow for passage of underfire air.⁷⁴ These air openings vary from approximately 2 to 30% of the grate surface area. The smaller air openings tend to limit the quantity of siftings dropping through the grates and create a pressure drop that assists in controlling the point of introduction of underfire air. RDF grates generally have a smaller

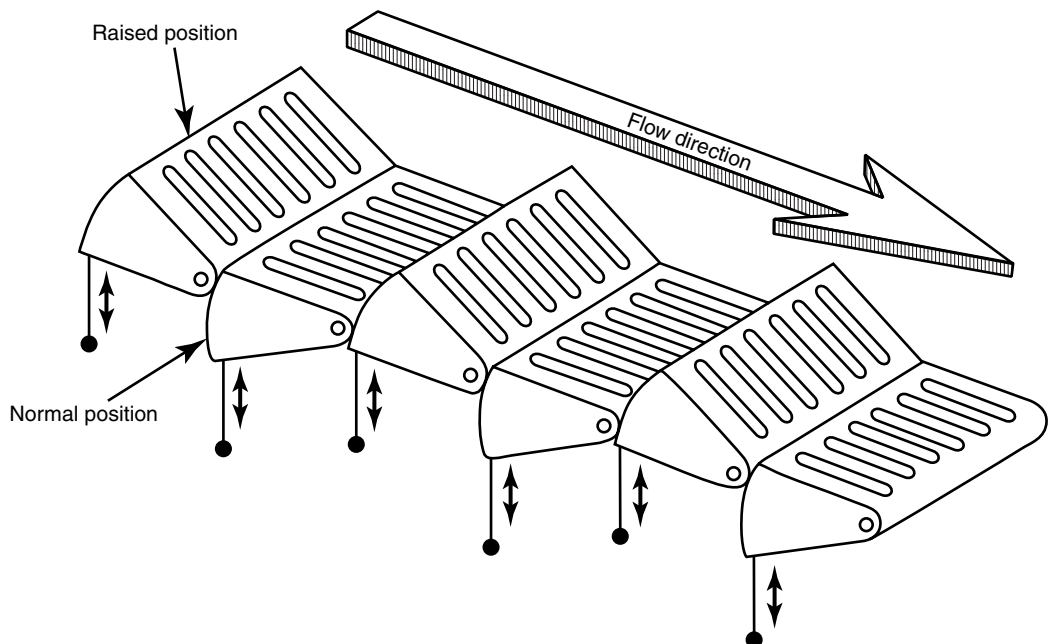


FIGURE 24.5 Rocking grates.

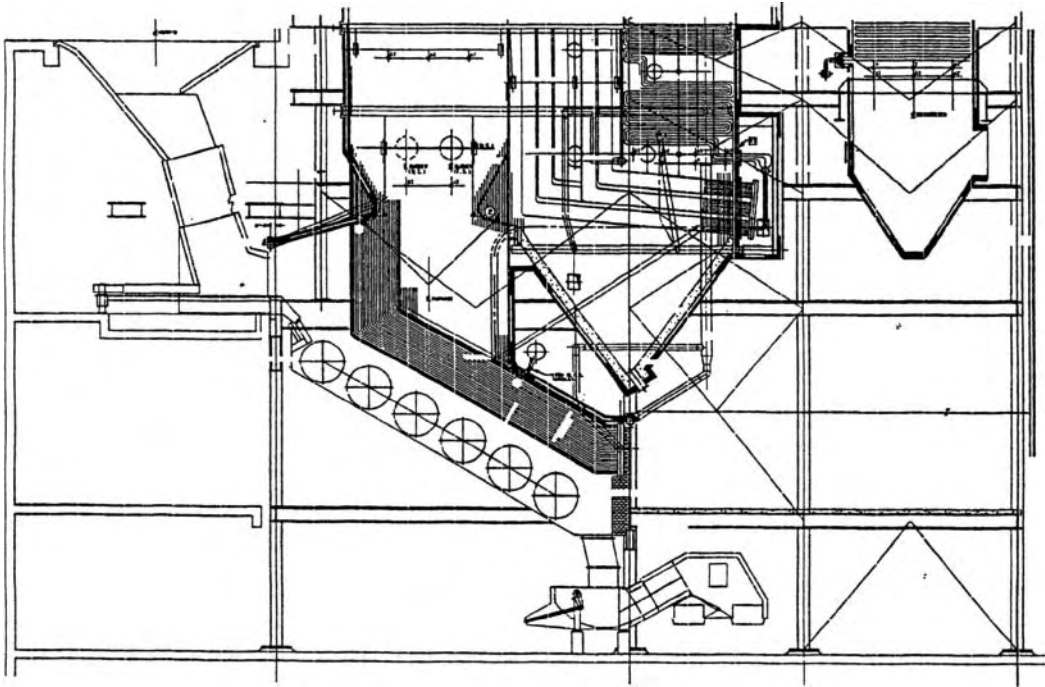


FIGURE 24.6 Roller grate system by Covanta Energy Group.

percentage of air openings. Larger air openings make control of underfire air more difficult but allow for continuous removal of fine material, which could interfere with the combustion process, from the fuel bed.

Furnace configuration is largely dictated by the type of grate used. In the continuous feed mechanical grate system, the furnace is rectangular in plan and the height is dependent upon the volume required by the limiting rate of heat release cited earlier. An optimum furnace configuration would provide sufficient volume for retention of gases in the high-temperature zone of maximum fuel volatilization long enough to ensure complete combustion, and would be arranged so that the entire volume is effectively utilized. Temperatures are usually high enough with present-day refuse for proper combustion. Turbulence should be provided by a properly designed overfire air system.

With present-day mass-fired water wall furnaces, the use of refractories in furnace construction has been minimized but not eliminated. Refractory materials may be used to line charging chutes, provide a transition enclosure between the top of the grates and the bottom of the water walls, a protective coating on the water wall tubes, and an insulating layer between the hot gases and the metal walls of flues downstream of the primary combustion chamber. Refractory brick used in a charging chute must be able to withstand high temperatures, flame impingement, thermal shock, slagging, spalling, and abrasion. The protective coating on the water wall tubes must be relatively dense castable material with a relatively high heat conductivity.⁷⁵ Insulating refractories used in flues downstream from the boilers, on the other hand, should have a low heat conductivity.

Refractories are generally classified according to their physical and chemical properties, such as resistance to chemical attack, hardness, strength, heat conductivity, porosity, and thermal expansion.⁵⁰ The material may be cast in brick in a variety of shapes and laid up with air-setting or thermal-setting mortar, or may be used in a moldable or plastic form. Material used in waste combustor construction includes “high duty” and “superduty” fireclay brick, phosphate-bonded alumina material, and silicon carbide, among others. In selecting the proper materials for application in this type of service, because the variety of materials is so great and the conditions of service so varied and severe,¹⁸ advice of a recognized manufacturer should be sought.

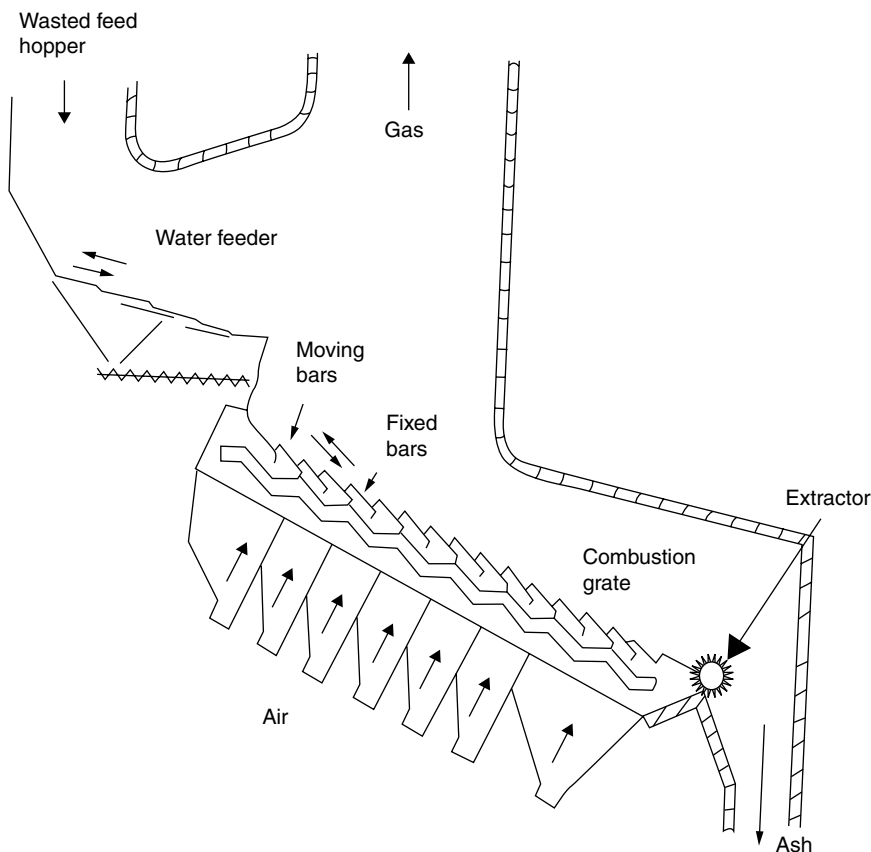


FIGURE 24.7 Martin system. (From Braun, H., Metzger, M., and Vogg, H. Zur Problematik der Quecksilber-Abscheidung aus Rauchgasen von Mullverbrennungsanlagen, Vol. 1, Teil 2.)

As indicated in the section on combustion calculations, the combustion process requires oxygen to complete the reactions involved in the burning process. The air that must be delivered in the furnace to supply the exact amount of oxygen required for completion of combustion is called the stoichiometric air requirement. Additional air supplied to the furnace is called excess air and is usually expressed as a percentage of the stoichiometric requirements.

The total air supply capacity in a waste combustor must be greater than the stoichiometric requirement for combustion because of imperfect mixing and to assist in controlling temperatures, particularly with dry, high heat-content refuse. The total combustion air requirements can range from 6 to 8 lb of air/lb of refuse for mass-fired water wall furnaces, and slightly less for RDF facilities.

In the modern mass-burn mechanical grate furnace chamber, at least two blower systems should be provided to supply combustion air to the furnace—one for underfire or undergrate air and the other for overfire air. Underfire air, admitted to the furnace from under the grates and through the fuel bed, is used to supply primary air to the combustion process and to cool the grates.

Overfire air may be introduced in two levels. Air introduced at the first level, called secondary air, immediately above the fuel bed, is used to promote turbulence and mixing, and to complete the combustion of volatile gases driven off the bed of burning solid waste. The second row of nozzles, which are generally located higher in the furnace wall, allow the introduction of air, called tertiary air, into the furnace to promote additional mixing of gases and for temperature control.

Blower capacities should be divided so that the underfire air blower is capable of furnishing half to two-thirds of the total calculated combustion air requirements, while the overfire blower should have a

capacity of about half of the total calculated air requirements. Setting these capacities requires some judgment related to assessing how great a variation is anticipated in refuse heat contents during plant operation. Variable frequency drivers on the fan motors or dampers on fan inlets and air distribution ducts should be provided for control purposes.

Pressures on underfire air systems in mass-burn units for most U.S. types of grates will normally range from 2 to 5 in. of water. European grates frequently require a higher pressure. The pressure on the overfire air should be high enough that the air, when introduced into the furnace, produces adequate turbulence without impinging on the opposite wall. This is normally accomplished by the use of numerous relatively small ($1\frac{1}{2}$ –3 in. in diameter) nozzles at pressures of 20 in. of water or higher.

Recirculated flue gas is sometimes used in part for underfire air and tempering air. Using recirculated flue gas as combustion air reduces the quantity of fresh air needed, thereby increasing thermal efficiency and minimizing thermal NO_x formation. It can also be used as tempering air to control the temperature of the flue gas entering the boiler.¹⁴ The duct work for recirculated flue gas is highly susceptible to corrosion due to the presence of acid gases. For this reason, it is critical that the recirculated gas be taken from the system after the pollution control devices.

In an RDF-fired, spreader-stoker type of unit, the combustible material is generally introduced through several air-swept spouts in the front water wall, is partially burned in suspension, and then falls onto a grate on which combustion is completed as the partially burned material is conveyed to the residue discharge under the front water wall face of the furnace. Densified RDF can also be burned in such units. The RDF can furnish all the combustible input to the system, or it may be co-fired with a fossil fuel, generally coal.

Some combustion air in RDF-fired units is introduced with the fuel through the air-swept feed spouts to distribute the fuel on the grate. Additional air is introduced into the furnace higher in the water wall area to enhance turbulence and mixing in the unit and/or to control temperatures. This additional combustion air supply is similar to the tertiary air utilized in the mass-burn units.

24.3.5 Boilers

Substantial quantities of heat energy may be recovered during the thermal destruction of the combustible portions of MSW. Systems that have been successfully used to recover this energy include mass-fired refractory combustion chambers followed by a convection boiler section; a mass-fired water wall unit where the water wall furnace enclosure forms an integral part of the boiler system and an RDF semisuspension-fired spreader-stoker/boiler unit. Each system has apparent advantages and disadvantages.

24.3.5.1 Refractory Furnace with Waste Heat Boiler

In a refractory furnace waste heat boiler unit, energy extraction efficiencies are generally lower, assuming the same boiler outlet temperatures, than with the other systems. Approximately 50%–65% of the heat generated in the combustion process may be recovered with such systems. These units can produce approximately 2–3 lbs steam/lb of normal MSW (heat content = 4500 Btu/lb), versus 3 or more lb/lb MSW in mass-fired water wall units. This lower efficiency of steam generation is caused by larger heat losses due to higher excess air quantities needed with such units to control furnace temperatures so that furnace refractories are not damaged. However, the boilers in such units, if properly designed and operated, generally are less susceptible to boiler tube metal wastage problems than the other systems listed earlier.

24.3.5.2 Mass-Fired Water Wall Units

Mass-fired water wall units are the most widely utilized type of heat recovery unit in this field today. In this type of unit, the primary combustion chamber is fabricated from closely spaced steel tubes through

which water circulates. This water wall lined, primary combustion chamber incorporated into the overall boiler system is followed by a convection type of boiler surface. It has been found desirable in these plants to coat a substantial height of the primary combustion chamber, subject to higher temperatures and flame impingement, with a thin coating of a silicon carbide type of refractory material or inconel and to limit average gas velocities to under 15 ft./s (4.5 m/s) in this portion of the furnace. Gas velocities entering the boiler convection bank should be less than 30 ft./s (9.0 m/s).⁷⁵ Efficiency of heat recovery in such units has been found to range generally from 65 to 75%, with steam production usually above 3 lb of steam/lb of normal as-received MSW. Water table studies have been used occasionally in some larger units to check on combinations of furnace configuration and location of overfire combustion of air nozzles.²⁹

24.3.5.3 RDF-Fired Water Wall Units

As pointed out earlier, RDF may be burned in a semisuspension-fired spreader-stoker/boiler unit where the RDF is introduced through several air-swept spouts in the front water wall, partially burns in suspension, and then falls on a grate on which combustion is completed. In this type of unit, the water wall lined primary combustion enclosure (furnace) may be followed by a superheater (usually), a convection boiler heat transfer surface, and (sometimes) an economizer surface.

Efficiencies of RDF-fired boilers generally range from 65 to 80% of the heat input from the RDF. Steam production from RDF would normally be expected to be somewhat greater than 3 lb of steam/lb of RDF. However, when one takes into account the combustible material lost in the processing of as-received MSW to produce the RDF, steam production normally will fall to about 3 lb of steam/lb of as-received MSW.³⁷

If the energy recovered from the combustion of as-received MSW or RDF is to be used to produce electricity, some superheating is desirable, if not necessary. Since boiler tube metal wastage in these plants is, at least partially, a function of tube metal temperature¹¹ and steam is a less efficient cooling medium than water, superheater surface is more prone to metal wastage problems than other areas of boiler tubing. Tube metal temperatures, above which metal wastage can be a significant operational problem, are generally thought to range from 650 to 850°F (345°C–455°C). These temperatures are lower than those for maximum efficiency of electrical generation by steam driven turbines. It is desirable to consider this in facility design to reduce plant downtime and minimize maintenance costs.

In the 1980s and early 1990s a so-called full-suspension combustion concept was attempted in which finely shredded combustible material from MSW was blown into the furnace through nozzles located one-half to two-thirds up the height of the water wall furnace enclosure. In this type of unit most of the RDF, usually composed of smaller sized particles than in the semisuspension-fired unit was supposed to burn in suspension. This concept was not successful due to problems related to the additional handling of the RDF and greater power required to achieve a finer shred. Also, some boilers seemed to experience a greater tendency for slag formation in the boiler. While the concept initially anticipated that the RDF would completely burn in suspension, experience indicated that this does not occur. Accordingly, dump grates became a necessity in such furnace boiler units to allow for completion of combustion prior to water quenching of the residue. This concept has been abandoned.

24.3.6 Residue Handling and Disposal

The residue from a well-designed, well-operated mass-fired incinerator burning as-received refuse will include the noncombustible material in the MSW and usually somewhat less than 3% of the combustibles. The nature of this material will vary from relatively fine, light ash, burned tin cans, and partly melted glass to large, bulky items such as lawn mowers and bicycles.

In most modern WTE plants bottom ash residue is discharged from the end of the furnace grate through a chute into a trough filled with water. Removal from the trough may be either by a ram discharger onto a conveyor or by a flight conveyor to an elevated storage hopper from which it is

discharged to a truck. If a water-filled trough with a flight conveyor is used, normally two troughs are provided, arranged so that the residue can be discharged through either trough. The second trough serves as a standby. Fly ash, residue collected in the air pollution control equipment downstream of the furnace/boiler, is usually returned back to and mixed with the bottom ash.

A key feature in the design of ash discharge facilities is provision for sealing the discharge end of the furnace to prevent uncontrollable admission of air. This seal is usually provided by carrying the ash discharge chute at least 6 in. (15 cm) below the water surface in the receiving trough. In the design of the conveyor mechanism, the proportions should be large because the material frequently contains bulky metal items and wire, potential causes of jamming. Also, the residue material tends to be extremely abrasive. A grizzly screen is often used to remove oversized bulky materials from the residue prior to its being loaded onto trucks for delivery to the landfill.

Residue is usually taken to a landfill for final disposal. Many modern facilities dispose of their residue at monofills (landfills that accept WTE plant residue only). The volume of material remaining for ultimate disposal will range from 5 to 15% of that received at the plant. Many plants currently operating in the United States that weigh MSW received at the plant and residue discharged from the furnaces, indicate that the weight of MSW is only reduced by from 40 to 50%. However, as much a one-third of the residue weight in these plants may be attributed to incomplete drainage of the material prior to its discharge into the final transportation container. The ram-type ash discharger used in European and most large U.S. plants generally achieves much better dewatering of residues than older water-filled trough, ash drag residue handling systems. These systems can achieve 65%–75% weight reduction.

The main components of ash are inert materials of low solubility, such as silicates, clay, and sand. Aluminum, calcium, chlorine, iron, selenium, sodium, and zinc are major elements in all particles and, along with carbon, can comprise over 10% by weight of the ash.²²

A broad range of trace metals and organic compounds may be found in fly and bottom ash. Data on ash composition are difficult to compare, however, because they reflect different types and sizes of facilities, unknown sample collection methodology and sample size at each facility, interlab variation in testing procedures (even using the same test), and the heterogeneous nature of MSW itself. In addition, the presence of a substance in ash does not mean that it will enter the environment. Its fate depends on its solubility, how the ash is managed, and whether the ash is subject to conditions that cause leaching.⁴⁸

Metals tend to be distributed differently in fly and bottom ash. Most volatile and semivolatile metals, such as arsenic, mercury, lead, cadmium, and zinc, tend to be more concentrated or “enriched” in fly ash.^{59,71} Less volatile metals, such as aluminum, chromium, iron, nickel, and tin, typically are concentrated in bottom ash.^{58,59}

Organic chemicals also exhibit differing distributions. Dioxin/furan and polychlorinated biphenyls (PCBs) tend to be enriched in fly ash, while other chemicals such as polycyclic-aromatic hydrocarbons (PAHs) and phthalates tend to be concentrated in bottom ash.⁷¹ Concentrations of dioxins/furans in fly ash exhibit a wide range, but they are significantly lower in ash from modern facilities than in ash from older incinerators.^{34,72,80}

From a regulatory standpoint, a number of different testing procedures have been developed and utilized by regulatory agencies over the past several years in an attempt to predict the behavior of MSW residues deposited in landfills. Most of these methods were developed to predict leaching characteristics of residues deposited in landfills with raw or as-received MSW. Test results using these methods have been quite variable. However, as pointed out earlier, most modern WTE facilities dispose of their residue in monofills.⁶⁸ Tests of leachate from such monofills indicate metals concentrations below extraction procedure (EP) toxicity limits, and in most cases below U.S. drinking water standards.⁶⁸ Most test data show little or no leaching of organic chemicals.^{35,68}

Following a court decision in the mid-1990s that ash residue from combustion of MSW is not exempt from the rules and regulations for hazardous waste, regulators have required testing of ash residues as they are discharged from the plant, i.e., separately if bottom ash and fly ash are discharged separately, and combined if they are combined prior to discharge from the plant. Bottom ash is alkaline and usually tests as nonhazardous, while fly ash is acidic and frequently tests as hazardous. When the fly ash is mixed with

bottom ash prior to discharge from the plant, the alkaline bottom ash neutralizes the smaller quantities of acidic fly ash. The mixture tests as nonhazardous and can be disposed of in the normal monofill.

24.3.7 Other Plant Facilities

The balance of the plant equipment is similar to that used in fossil fuel-fired boiler facilities. However, there are differences. Thus, the combustion of MSW produces a highly corrosive environment for boiler tube materials. Metal chlorides are believed to be primarily responsible for boiler tube corrosion problems.⁴³ The most important factors in high temperature corrosion are metal temperature, gas temperature, temperature gradient between gas temperature and metal temperature, deposit characteristics, and temperature fluctuations.¹ For this reason, boiler tubes are generally fabricated using corrosion-resistant alloys. Boiler tube shields or weld overlay cladding of boiler tubes with inconel are also used in highly corrosive/erosive areas.⁴³

Some waste-to-energy facilities incorporate an air heater to preheat combustion air. Finned tubes plug quickly due to the large quantity of flyash in the flue gas. These air heaters are always of the bare tube design.

Since thermal efficiency is not an overriding concern in waste-to-energy facilities, many plants have one, or at most two, feedwater heaters. Some have only a deaerator for feedwater heating, unlike conventional power plants which have several stages of feedwater heaters.

24.4 Air Pollution Control Facilities

Potential emissions from the combustion of MSW may be broadly classified into particulates, gaseous emissions, organic compounds, and trace metals. The concern is to reduce emissions so as to adequately protect public health. This is achieved using good combustion practice and equipment specially designed to remove the targeted pollutants.

During the 1980s and 1990s, the emission requirements for air pollution control equipment became more stringent as the USEPA promulgated new standards. The most recent standards were published in the December 19, 1995 Federal Register as 40 CFR Part 60 Subpart Cb^{6,73}. These standards established emission limits for large (over 248 tons per day [225 Mg/d]) and small (under 248 tons per day [225 Mg/d]) combustor units. [Table 24.10](#) and [Table 24.11](#) contain a summary of those standards.

24.4.1 Particulate Control

Particulates have been a matter of concern and regulatory agency attention for some time. The initial concern was from the standpoint of reducing gross particulate emissions that were both an aesthetic and a potential public health problem. Current interest and concern is directed toward better control of submicron-size particles⁷⁶ and other pollutants.

Electrostatic precipitators were the most commonly used gas cleaning device for particulate emission control in municipal waste combustors in the 1970s and early 1980s. They were designed to achieve high collection efficiencies (99% or higher) and meet the air emissions standards at the time. As emission standards became more stringent for particulates, fabric filters became more prevalent. Many electrostatic precipitators were replaced with fabric filters due to the 1995 regulations.

Fabric filters can operate at high efficiency, even in the submicron particle size range. They became widely used in the late 1980s because of the increasing emphasis of regulatory agencies on acid gas control and lower particulate emission levels. Baghouses are more effective than electrostatic precipitators for acid gas scrubbing when preceded by a spray dryer. The original bags used in these facilities had a limited life at high temperatures. Experiments using different materials of construction have led to longer bag life.

The scrubber/fabric filter control systems have been shown to be capable of operating at a particulate emission level of 20 mg/Nm³ (0.009 gr/dscf) and lower (see [Table 24.12](#)). The material selected for the

TABLE 24.10 Emission Limits for Large Combustor Units

Parameter	Limit	Conditions
Particulates	27 mg/DSCM	Corrected to 7% oxygen
Opacity	10%	6-min average
Cadmium	0.04 mg/DSCM	Corrected to 7% oxygen
Lead	0.49 mg/DSCM	Corrected to 7% oxygen
Mercury	Lesser of 0.08 mg/DSCM or 85% removal	Corrected to 7% oxygen
SO ₂	Lesser of 31 ppmv or 75% removal	Corrected to 7% oxygen 24-hour geometric mean
HCl	Lesser of 31 ppmv or 95% removal	Corrected to 7% oxygen
Dioxin/furans	60 ng/DSCM—ESP 30 ng/DSCM—all others	Corrected to 7% oxygen
NO _x	220 ppmv—water wall	Corrected to 7% oxygen
	250 ppmv—rotary water wall	Corrected to 7% oxygen
	250 ppmv—RDF	Corrected to 7% oxygen
	240-fluidized bed	Corrected to 7% oxygen

filter bags can have an important effect on filtering efficiency and the emission level thus achieved. In general, test results to date for the scrubber/fabric indicate lower particulate emissions than those for electrostatic precipitators on WTE plants. However, in general, electrostatic precipitators have not been designed to meet emission levels as low as those specified for fabric filter installations. Electrostatic precipitators following spray drying absorbers in Europe have been tested at particulate emission levels of 1–8 mg/Nm³ (0.00045–0.0036 gr/dscf). The reliability and overall economics of the various control processes must be considered when making a selection of equipment to meet these very low emission control requirements. Data are available⁶⁸ on emission levels for approximately 30 different specific elements, many of them heavy metals. Elements found to occur in stack emission from municipal waste combustors are lead, chromium, cadmium, arsenic, zinc, antimony, mercury, molybdenum, calcium, vanadium, aluminum, magnesium, barium, potassium, strontium, sodium, manganese, cobalt, copper, silver, iron, titanium, boron, phosphorus, tin, and others.

Since the condensation point for metals such as lead, cadmium, chromium, and zinc is above 570°F (300°C), the removal efficiency for such metals is highly dependent on the particulate removal efficiency. Some metal compounds, particularly chlorides such as AsCl₃ at 252°F (122°C) and SnCl₄ at 212°F (100°C), have condensation points below 300°C. For such compounds, particulate collection

TABLE 24.11 Emission Limits for Small Combustor Units

Parameter	Limit	Conditions
Particulates	70 mg/DSCM	Corrected to 7% oxygen
Opacity	10%	6-min average
Cadmium	0.10 mg/DSCM	Corrected to 7% oxygen
Lead	1.6 mg/DSCM	Corrected to 7% oxygen
Mercury	Lesser of 0.08 mg/DSCM or 85% removal	Corrected to 7% oxygen
SO ₂	Lesser of 80 ppmv or 50% removal	Corrected to 7% oxygen 24-hour geometric mean
HCl	Lesser of 250 ppmv or 50% removal	Corrected to 7% oxygen
Dioxin/furans	125 ng/DSCM	Corrected to 7% oxygen
NO _x	No limit	Corrected to 7% oxygen

TABLE 24.12 Particulate Emissions from Municipal Waste Combustors

	Particulates (gr/dscf) ^a @ 12% CO ₂
Plant G (1983); EP	0.0321
Plant T (1984); DS, BH	0.012
Plant M (1984); DS, EP	0.0104
Plant W (1985); DS, BH	0.004
Plant P (1985); EP	0.0163
Plant T (1986); EP	0.007
Plant M (1986); DS, BH	0.007

EP, electrostatic precipitator; DS, dry scrubber; BH, bag house.

^a Grains per dry standard cubic foot.

Source: From Velzy, C. O. 1987. *U.S. Experience in Combustion of Municipal Solid Waste*, Atlanta, GA, February 20.

temperatures will be a factor in collection efficiency. High removal (over 99%) has been observed for most metals for highly efficient (over 99%) particulate removal systems operating at appropriate temperatures.

24.4.2 Gaseous Emission Control

Gaseous emissions such as SO₂, HCl, CO, NO_x and hydrocarbons have recently become a concern in municipal waste combustors and their emissions are now regulated. Acid gas emissions are controlled by scrubbing devices. Carbon monoxide, NO_x, and hydrocarbons are controlled by good combustion practice. Oxides of nitrogen in some cases also require control equipment in the form of selective noncatalytic reduction (SNCR) to reduce NO_x to acceptable levels.

Common gaseous emission factors, based on tests at a number of waste-to-energy plants, are shown in Table 24.13. High carbon monoxide and hydrocarbon emissions are caused by incomplete combustion and/or upsets in combustion conditions. High nitrogen oxide emissions are generally caused by high combustion temperatures. Hydrogen chloride (and hydrogen fluoride) and sulfur oxides, on the other hand, are directly a function of the chlorine (fluorine) and sulfur content in the fuel. The highest emissions, cited in Table 24.13, are from older, poorly controlled plants without significant pollution control equipment.

TABLE 24.13 Gaseous Emission Factors for Municipal Waste Combustors (lb/ton)

	New York Incinerators 1968–1969	Test Results U.S. Plants 1971–1978	Martin Plants 1984–1986	EPA Data Base Tests Through 1988	
				Mass-Burn	RDF
Carbon monoxide	—	3.7–9.3	0.2	0.06–16.2	1.0–5.2
Nitrogen oxides	—	0.5–2.2	5.0–6.0	0.5–4.5	2.5–3.2
Hydrocarbons	0.1–22.1	1.1	0.015–0.006	0.01–0.1	0.005–0.01
Hydrochloric acid	1.4–8.6	4.6–14.5	5.0–0.2	0.05–5.7	0.02–9.3
Sulfur oxides	1.3–8.0	0.8–2.2	1.0–2.0	0.05–4.8	0.05–2.3

Source: From Carrotti, A. A. and Smith, R. A. 1974. *Gaseous Emissions from Municipal Incinerators*; Cooper Engineers, Inc. 1985. *Air Emissions Tests of a Deutsche Babcock Anlagen, Dry Scrubber System at the Munich North Refuse-Fired Power Plant*; Hahn, J. L., VonDemfange, H. P., Zurlinden, R. A., Stianche, K. F., Seelinger, R. W. (Ogden Martin Systems, Inc.), and Weiland, H., Schetter, G., Spichal, P., and Martin, J.E. (Martin GmbH), 1986. *National Waste Processing Conference*, Denver, CO, June 1–4, 1986. ASME, New York; Murdoch, J. D. and Gay, J. L. 1989. *Material Recovery with Incineration, Monmouth County, N.J.*, p. 329, Tulsa, OK, August 14–17; Velzy, C. O. 1985. *Standards and Control of Trace Emissions from Refuse-Fired Facilities*, Madison, WI, November 20–22.

Hydrogen chloride (and hydrogen fluoride) and sulfur oxides are best removed by acid gas scrubbing devices using chemical treatment. Initial efforts at acid gas control used wet collectors. However, this type of flue gas cleaning equipment is subject to problems such as corrosion, erosion, generation of acidic waste water, wet plumes, and, not least, high operating cost. Because of these problems, various semiwet and dry methods of cleaning flue gases have been developed and installed. These methods of gas treatment are based on the injection of slurried or powdered lime, limestone, or dolomite; adsorption; and absorption; followed by chemical conversion.⁶⁸ Since the reactivity of these lime materials is rather low, a multiple of the stoichiometric quantity is normally required to obtain a satisfactory cleaning effect. High removal efficiencies can be achieved for HCl, but reduction of SO₂ and SO₃ is more difficult to achieve and maintain. Slaked lime is highly reactive and stoichiometric ratios of 1.2–1.7 have been used for 97%–99% HCl removals and 60%–90% SO₂ reductions, depending on operating conditions and particulate collector (fabric filters having demonstrated higher removal efficiencies than electrostatic precipitators).

Lime injection into a scrubber/fabric filter system has resulted in removal efficiencies of 90%–99% for HCl and 70%–90% SO₂, provided that the flue gas temperature and the stoichiometric ratio for lime addition are suitable. This combination of processes has reduced HCl levels below 20 ppm and SO₂ to levels below 30 ppm for MSW waste-to-energy plants. This technology has also been extensively used in other applications for acid gas removal. The scrubber/electrostatic precipitator combination has been shown to provide about 90% HCl removal, but typically less SO₂ removal (about 50%). Since this removal efficiency does not meet the most recent regulations, many electrostatic precipitators have been replaced with baghouses. Lime injection into the furnace has also been tested with some success (about 50%–70% efficiency), but fails to meet the most recent regulations.

Some sampling to determine HF removal has been reported. In general, HF removal normally follows HCl removal (i.e., is usually over 90%–95%).

Carbon monoxide and hydrocarbon emissions are best controlled by maintaining proper combustion conditions. Nitrogen oxide emissions are controlled by ammonia injection or by use of combustion control techniques such as limitation of combustion temperatures or recirculation of flue gases. Note in the last column of [Table 24.13](#) that attempts to limit hydrocarbon emissions by improving combustion conditions and raising furnace operating temperatures seem to have resulted in increasing the level of NO_x emissions.

Selective noncatalytic reduction (SNCR) appears to be the most practical method of reducing NO_x emissions for most municipal waste combustors. SNCR involves the use of ammonia to reduce NO_x to nitrogen and water. The SNCR reaction occurs at a temperature of 1600°F–2100°F. At lower temperatures, a catalyst is required to promote the reaction (selective catalytic reduction, or SCR). SCR is not used on municipal waste combustors. Tests conducted at a municipal waste combustor demonstrated that NO_x emission levels of 150 ppmv (45%–55% reduction) can be achieved with SNCR.⁶

Thermodynamic equilibrium considerations indicate that under excess air conditions and with temperatures of 1472°F (800°C) and higher, maintained in a completely mixed reactor for a suitable period of time, emissions of organic or hydrocarbon compounds should be at nondetectable levels. However, measurements at operating plants, particularly those constructed prior to the early to mid-1980s, indicated significant emissions of trace organic or hydrocarbon compounds, some of which are toxic. These tests indicated that the basic objective of combustion control, thorough mixing of combustion products with oxygen at a temperature that is sufficiently high to provide for the rapid destruction of all organic or hydrocarbon compounds, had not been achieved in these early WTE plants.

If the fuel, or the gas driven off of the fuel bed, is not adequately mixed with air, fuel-rich pockets will exist containing relatively high levels of hydrocarbons, which then can be carried out of the combustion system. Kinetic considerations indicate that such hydrocarbons can be destroyed rapidly in the presence of oxygen at elevated temperatures. Also, if too much combustion air is introduced into the combustion chamber, either in total or in a particular area of the chamber, temperatures will be reduced, combustion reactions can be quenched, and hydrocarbons carried out of the combustion system. Achieving the goal

of proper combustion control, destruction of all hydrocarbon compounds to form carbon dioxide and water, will minimize emission of potentially toxic substances as well as other compounds that may be precursors and capable of forming toxic compounds downstream in cooler regions of the boiler.

Table 24.13 shows that the hydrocarbons can vary significantly, frequently over relatively short periods of time, based on measurements at older municipal waste combustors. The highest levels shown in this table occurred in one of the older plants and no doubt indicate very poor combustion conditions. Tests at modern WTE plants indicate consistently low levels of hydrocarbons, which are indicative of good combustion control. In modern, well-designed and -operated plants, photochemical oxidants and PAH are in concentrations too low to cause any known adverse health effects. Tests^{55,66} for other substances that might be of concern, such as polychlorinated biphenyls (PCBs), generally have found levels discharged to the atmosphere to be so low as to have a negligible impact on the environment.

24.4.3 Organic Compound Control

Organic compounds for which emission data are available include polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), chlorobenzenes (CBs), chlorophenols (CPs), polycyclic aromatic hydrocarbons (PAHs), and PCBs. A number of other organic compounds, including aldehydes, chlorinated alkanes, and phthalic acid esters, have also been identified in specific testing programs. Since dioxin/furan emissions have generated the most interest over the past several years, there are more data for these compounds, in particular for the tetrahomologues, and especially the 2,3,7,8-substituted isomers. The other compounds have been less frequently reported in the literature. The reason for this emphasis is the toxicity of dioxin/furan to laboratory animals and the perceived risk to humans.

Upset conditions in energy-from-waste plants can lead to local air-deficient conditions resulting in the emission of organic compounds. PAHs are formed during fuel-rich combustion as a consequence of free radical reactions in the high temperature flame zone. In addition, it is found that in the presence of water cooled surfaces, such as found in oil-fired home-heating furnaces, a high fraction of the polycyclic compounds are oxygenated. Similar free radical reactions probably take place in fuel-rich zones of incinerator flames yielding PAH, oxygenated compounds such as phenols, and, in the presence of chlorine, some dioxin/furan. The argument for the synthesis of dioxin/furan at temperatures of 400°F–800°F is supported by the increase in the concentration of these pollutants across a heat recovery boiler downstream of the refractory lined combustion chamber of a waste combustor.

This free radical mechanism appears to be the dominant source of dioxin/furan in municipal waste combustors. These compounds may also be present as contaminants in a number of chemicals, most notably chlorinated phenols and polychlorinated biphenyls (PCBs). Their presence in MSW results from the use of these chemicals, discontinued in some cases, as fungicides and bactericides for the phenol derivatives, or the use of PCBs as heat exchanger and capacitor fluids. These compounds are expected to survive in a furnace combustion chamber only if large excesses in the local air flow cool the gases to below the decomposition or reaction temperature. Dioxin/furan can also be produced by condensation reactions involving the chlorinated phenols and biphenyls. The observed formation of dioxin/furan when fly ash from MSW incinerators is heated to temperatures of 480°F (250°C) suggest such catalyzed condensation reactions of chlorinated phenols. PCBs are precursors to furan, and pyrolysis of PCBs in laboratory reactors at elevated temperatures for a few seconds has yielded furan.

The available test data clearly show that dioxin/furan exit the boilers and, depending on the emission control devices employed, some fraction enters the atmosphere either as gases or adsorbed onto particulates. In addition, the solids remaining behind in the form of fly ash and bottom ash contain most of the same compounds, and these become another potential source of discharge to the environment.

Emission data for total dioxin/furan generally fall into three main categories:

- Low emissions, in the range of 20–130 ng/Nm³

- Medium emissions, from 130 to 1000 ng/Nm³
- High emissions, over 1000 ng/Nm³

Average dioxin/furan emission from older plants ranges from about 500 to 1,000 ng/Nm³. The lower emission levels tend to be associated with newer, well-operated mass-fired facilities such as water wall plants, and with modular, starved or controlled air types of incinerators (see Table 24.14). In most test programs, adequate operating data were not collected to correlate emissions with operations. Researchers in the field theorize that combustion conditions can play a role in minimizing emissions, and several studies^{63,68,70} were conducted in Canada and the United States to define that role more exactly.

Emissions from MSW combustion contain small amounts of many different dioxin/furan isomers. While individual dioxin/furan isomers have widely differing toxicities, the 2,3,7,7-TCDD isomer, present as a small proportion of the total dioxin/furan, is of greatest known toxicological concern. Based on animal studies it has been generally concluded that other 2,3,7,8-substituted dioxin/furan isomers, in addition to the 2,3,7,8-TCDD, are also likely to be of toxicological concern. A method for expressing the relative overall toxicological impact of all dioxin/furan isomers, as so-called “2,3,7,8-TCDD toxic equivalents,” was developed in the mid-1980s⁴ and has been used by the EPA intermittently in its regulatory efforts since this time.

In this method, emissions are sampled, extracted, and analyzed for all constituent isomers of dioxin/furan. A system of toxicity weighting factors from the existing toxicological data (based almost entirely on animal studies) is applied to each constituent dioxin/furan isomer and the results are summed to arrive at the 2,3,7,8-TCDD toxic equivalent. An example of dioxin/furan test results expressed as 2,3,7,8-TCDD toxic equivalents, using three different systems of weighting factors, is shown in Table 24.15.

Emission control systems consisting of a scrubber/fabric filter have been evaluated for dioxin emissions.³⁶ Recently dioxin removal efficiencies exceeding 99% were obtained, which resulted in dioxin concentrations at the stack that approach the detection limit of the sampling and analytical equipment currently available. Emissions of furan followed a similar range of values as dioxin with the scrubber/high efficiency particulate removal combination reducing furan to very low or nondetectable levels. Additional reductions of over 50% can be achieved by activated carbon injection.⁶

Some limited data on emissions of CB, CP, PCB, and PAH are available. Most sampling programs for dioxin/furan have unfortunately neglected to analyze for these compounds. Maximum levels from Canadian studies³⁶ are as included in Table 24.16 along with some data from tests on U.S. plants.³⁵ The scrubber/fabric filter technology generally demonstrated removal rates of 80%–99% for these compounds in these studies.

TABLE 24.14 Summary of Average Total PCDD/PCDF Concentrations from MSW Combustion in Modern Plants (ng/Nm³, dry, at 12% CO₂)

	Total PCDD + PCDF
Peekskill, NY, electrostatic precipitator only (1985)	100.25
Wurzburg, FRG, dry scrubber-baghouse (1985)	49.95
Tulsa, OK, electrostatic precipitator only (1986)	34.45
Marion Co., OR, dry scrubber-baghouse (1986)	1.55

Source: From Hahn, J. L., VonDemfange, H. P., Zurlinden, R. A., Stianche, K. F., Seelinger, R. W. (Ogden Martin Systems, Inc.), and Weiand, H., Schetter, G., Spichal, P., and Martin, J. E. 1986. *(Martin GmbH) 1986 National Waste Processing Conference*, Denver, CO, June 1–4, ASME, New York; NYS Department of Environmental Conservation Bureau of Toxic Air Sampling, Division of Air Resources. 1986. *Preliminary Report on Westchester RESCO RRF*, January 8; Ogden Projects, Inc. 1986. *Environmental Test Report, Walter B. Hall Resource Recovery Facility*, October 20; Ogden Projects, Inc. 1986. *Environmental Test Report, Marion County Solid Waste-to-Energy Facility*, December 5.

TABLE 24.15 Toxic Equivalent emissions by U.S. EPA, Swedish, and California Methods⁸³

Facility	Toxic Equivalents ng/Nm ³ at 12% CO ₂		
	U.S. EPA	Swedish	California
Peekskill, NY	1.62	3.83	9.73
Tulsa, OK	0.7	1.74	4.75
Wurzburg, FRG	0.37	0.81	2.11
Marion Co., OR	0.11	0.16	0.29
From WHO Workshop; Naples, Italy			
Max. from avg. oper.	25.0	52.78	134.5
Achievable with no acid gas cleaning	0.9	2.2	5.94

Source: From Hahn, J. L., Sussman, D. B. 1986. *Dioxin Emissions from Modern, Mass-Fired, Stoker/Boilers with Advanced Air Pollution Control Equipment*. Fukuoka, Japan, September; NYS Department of Environmental Conservation Bureau of Toxic Air Sampling, Division of Air Resources. 1986. *Preliminary Report on Westchester RESCO RRF*, January 8; Ogden Projects, Inc. 1986. *Environmental Test Report, Walter B. Hall Resource Recovery Facility*, October 20; Ogden Projects, Inc. 1986. *Environmental Test Report, Marion County Solid Waste-to-Energy Facility*, December 5; World Health Organization. 1986. Report on PCDD and PCDF Emissions from Incinerators for Municipal Sewage, Sludge and Solid Waste—Evaluation of Human Exposure, from WHO Workshop, Naples, Italy, March.

Very few studies report on other organic products in the flue gas. Some data from tests on older plants have been reported for aldehydes and certain other volatile hydrocarbons.⁵ Such data are not available for newer plants.

The conventional combustion gas measurements include CO, total hydrocarbons (THCs), CO₂, and H₂O. Both CO and THC have been of interest as potential surrogates for dioxin/furan emissions; however, no strong correlations have been found in previous studies. In fact, very few studies have attempted to determine CO and dioxin/furan emission data for several operating conditions on the same combustor to develop a correlation. On the other hand, several authors have attempted to correlate CO and dioxin/furan data obtained from several different facilities. From such comparisons, it appears that low CO levels (below 100 ppm) are associated with low dioxin/furan emissions.⁴¹ High CO levels of several 100 ppm and even over 1000 ppm have been associated with high dioxin/furan emissions. During poor or upset combustion conditions, CO levels of several thousand ppm have been observed and THC levels have risen from a typical 1–5 ppm to 100 ppm and more. Since one of the measures available to combustor operators to optimize combustion control is to minimize CO production, one would assume from these general correlations that this would also tend to minimize dioxin/furan emissions, along with emissions of other trace chlorinated hydrocarbons. THC is not as useful as CO as an indicator of proper

TABLE 24.16 Organic Emissions (ng/Nm³)

Chemical Emitted	U.S. Plants	Canadian Pilot Plant	
	Before Particulate Removal	Before Particulate Removal	After Scrubber/Fabric Filter
CB	10,000–500,000	17,000	3000
CP	22,000–80,000	30,000	8000
PCB	—	700	Nondetectable (ND)
PAH	ND to 5,600,000	30,000	130

Source: From Battelle Columbus Labs. 1982. *Characterization of Stack Emissions from Municipal Refuse-to-Energy Systems*. National Technical Information Service, PB87-110482, October.; Hay, D. J., Finkelstein, A., Klicius, R. (Environment Canada), and Marenlette, L. (Flakt Canada, Ltd.). The National Incinerator Testing and Evaluation Program: An Assessment of (A) Two-Stage Incineration (B) Pilot Scale Emission Control, Report EPS 3/UP/2, September 1986. Hay, D.J., Finkelstein, A., Klicius, R. (Environment Canada), and Marenlette, L. (Flakt Canada, Ltd.). 1986. The National Incinerator Testing and Evaluation Program: An Assessment of (A) Two-Stage Incineration (B) Pilot Scale Emission Control, Report EPS 3/UP/2, September.

TABLE 24.17 Lime Addition with Baghouse, Percent Removal of Organics

	Dry System				Wet/Dry System	
	110°C	125°C	140°C	200°C	140°C	140°C Recycle
CB	95	98	98	62	> 99	> 99
PCB	72	> 99	> 99	54	> 99	> 99
PAH	84	82	84	98	> 99	79
CP	97	99	99	56	99	96

Source: From Hay, D. J., Finkelstein, A., Klicius, R. (Environment Canada), and Marenlette, L. (Flakt Canada, Ltd.) 1986. The National Incinerator Testing and Evaluation Program: An Assessment of (A) Two-Stage Incineration (B) Pilot Scale Emission Control, Report EPS 3/UP/2, September.

combustion because of problems in sampling to consistently obtain a representative sample for analysis at the analytical instrument.

Table 24.17 shows operating results achieved using dry and semidry lime injection followed by a baghouse for removal of trace organic pollutants from waste combustor emissions.

24.4.4 Trace Metals

Trace metals are not destroyed during combustion, and the composition of wastes therefore provides, on a statistical basis, the measure of the total inorganic residue. The distribution of trace metals between bottom ash and ash carried over to the air pollution control device is dependent upon the design and operation of the combustor and the composition of the feed. The amount of ash carried up and with the flue gases discharged from a burning refuse bed increases with increasing underfire air rate and with bed agitation. Modular incinerators (described later in “Status of Other Technologies”) with low underfire air flow rates tend to have lower particulate emissions than conventional mass-burn units and RDF units for this reason. In addition, the amount of ash carried from the combustion chamber will be influenced by the particle size of the inorganic content of the MSW.

The distribution of trace metals between the different components of refuse has a strong influence on the fate of the trace metals. For example, TiO_2 used as a pigment in paper products, has a particle size of about 0.2 μm and will tend to be carried off by the flue gases passing through the refuse bed, whereas TiO_2 present in glass will remain with the glass in the bottom ash. Up to 20% of the inorganic content of the waste will be entrained from burning refuse beds to form fly ash particles. The remainder will end up in the residue.

Volatile metals and their compounds, usually present in trace amounts in the feed, will vaporize from the refuse and condense in the cooler portions of a furnace either as an ultra fine aerosol (size less than 1 μm) or on the surface of the fly ash, preferentially on the surface of the finer ash particles. A large fraction of certain elements in the feed, such as mercury, will be volatilized.

Since mercury is a very volatile metal, it exists in vapor phase at temperatures as low as 68°F–122°F (20°C–50°C). Several studies have indicated that sufficient cooling of the flue gas (typically below 140°C, based on test results conducted to date) and a highly efficient particulate removal system to remove the particles on which the mercury has been adsorbed^{8,10,81} are both required to achieve high mercury removal. High mercury removal has been obtained for the scrubber/fabric filter system, provided that the flue gas is adequately cooled (see Table 24.18).

Test results with carbon injection at two municipal waste combustors demonstrated that the EPA emission guidelines of 80 mg/dscm or 85% reduction in mercury emissions can be achieved with a spray dryer, fabric filter and carbon injection.⁶

Elements such as sodium (Na), lead (Pb), zinc (Zn), and cadmium (Cd), will be distributed between the volatiles and the residue in amounts that depend on the chemical and physical form in which the

TABLE 24.18 Lime Addition with Baghouse Mercury Concentrations ($\mu\text{g}/\text{km}^3$ @ 8% O_2)

Operation	Inlet	Outlet	%Removal
Dry System			
230°F (110°C)	440	40	90.9
260°F (125°C)	480	23	97.9
285°F (140°C)	320	20	93.8
390°F (> 200°C)	450	610	0
Wet-dry system			
140°C	290	10	94.7
140°C ← recycle	350	19	94.7

Source: From Hay, D. J., Finkelstein, A., Klicius, R. (Environment Canada), and Marenlette, L. (Flakt Canada, Ltd.). 1986. *The National Incinerator Testing and Evaluation Program: An Assessment of (A) Two-Stage Incineration (B) Pilot Scale Emission Control*, Report EPS 3/UP/2, September.

elements are present. For example, sodium in glass will be retained in the residue but that in common salt will partially disassociate and be discharged with the emission gases.

Some of the data on metal emissions that are available from tests on resource recovery plants is shown in Table 24.19. Note that the emission of trace metals can be dramatically limited at WTE plants by the use of high-efficiency particulate control devices that are installed on modern facilities.

While sampling for metal emissions is fairly well established, in order to obtain enough sample to analyze at highly controlled sources, samples times are extremely long, sometimes over 8 hours using the U.S. EPA Method 5 sample train (relatively low sample rate). Several studies^{30,31,44} of waste combustor emissions in the United States in the 1970s concluded that “municipal incinerators can be major sources of Cd, Zn, Sb and possibly Sn...” This conclusion is based on the relative concentration of these materials in the total suspended particulate catch. However, two of the three plants tested in these studies utilized inefficient air pollution control facilities. Thus, particulate emissions in these plants were relatively high when compared to the German and Japanese plant data in Table 24.19, which is similar to emission data from most modern mass-burn and RDF waste-to-energy plants in the United States.⁶⁸ Note also in Table 24.19 that, as the efficiency of particulate control improves, trace metal emissions generally decrease, and in most cases decrease significantly. Even though there is ample evidence from test data¹⁹ to indicate that heavy metals tend to concentrate on the finer particulates, there is also evidence from test results to show that at high particulate removal efficiency (99% \pm), high trace metal removal (99% \pm) is achieved. Thus, the conclusion in these studies of waste combustors quoted earlier is not valid for WTE plants utilizing efficient air pollution control devices.

The important operating parameters for such equipment are flue gas temperature and composition, contact time, relative velocity of particles and gas stream, and possible activation of particles. See Table 24.18 and Table 24.20 for operating results achieved using dry and semidry lime injection followed by a baghouse for removal of heavy metal pollutants from waste combustor emissions.

24.5 Performance

Mass burning of MSW is the most highly developed and commercially proven combustion process presently available for reducing the volume of MSW prior to ultimate disposal of residuals on the land, and for extracting energy from the waste.⁷¹ Hundreds of such plants, incorporating various grate systems and boiler concepts, which differ in details of design, construction, and quality of operation, have been built throughout the world since the mid-1960 s. Mass-burn systems are generally furnished with a guaranteed availability of 85%, while in practice availabilities of 90%–95% have been achieved.⁶⁸ Availability cannot approach 100% because standard maintenance practice requires periodic shutdowns.

TABLE 24.19 Trace Metal Emissions Test Results

	Japanese Plant Uncontrolled	Braintree Mass. Part. Rem. Eff. 74+ %	Particulate Removal Efficiency 99+ %				
			German Plants	Japanese Plants	Tulsa, OK	Dry Scrubber, Fab. Filter	
						Marion, Co., OR	Pilot Plant Canada
Arsenic (As) (lb/Ton $\times 10^{-3}$)	< 0.4	0.125	0.09	< 0.0016	—	—	0.00033–0.00064
Beryllium (Be) (lb/Ton $\times 10^{-3}$)	< 0.3	0.00027	0.002	< 0.0016 ^a	0.000025	0.000021	—
Cadmium (Cd) (lb/Ton $\times 10^{-3}$)	0.7	1.30	0.25	0.11	—	—	ND-0.006
Chromium (Cr) (lb/Ton $\times 10^{-3}$)	16.0	0.34	0.185	0.026	—	—	ND-0.016
Lead (Pb) (lb/Ton $\times 10^{-3}$)	17.0	42.4	10.0	0.1	3.5	0.29	ND-0.08
Mercury (Hg) (lb/Ton $\times 10^{-3}$)							
on particulates	0.5	0.11	0.067	0.03	—	—	—
vapor phase	0.8	4.38 ^a	—	0.90	3.5	2.9	0.16–9.83
Selenium (Se) (lb/Ton $\times 10^{-3}$)	< 0.3	—	—	< 0.0016	—	—	—
Particulates (lb/Ton)	25.7	1.3	0.5	0.19	0.13	0.16	< 0.01

^a Total on particulate and vapor phase.

Source: From Clark, L., *Case History of a 240 Ton Day Resource Recovery Project: Part II*, pp. 235–248, ASME, New York; Hahn, J. L. and Sofaer, D. S. 1988. *Variability of NO_x Emissions from Modern Mass-Fired Resource Recovery Facilities*, Dallas, TX, June; Ogden Projects, Inc. 1986. *Environmental Test Report, Walter B. Hall Resource Recovery Facility*, October 20.; Ogden Projects, Inc. 1986. *Environmental Test Report, Marion County Solid Waste-to-Energy Facility*, December 5.; Velzy, C. O. 1985. *Standards and Control of Trace Emissions from Refuse-Fired Facilities*, Madison, WI, November 20–22.

TABLE 24.20 Lime Addition with Baghouse, Metal Concentrations ($\mu\text{g}/\text{km}^3$ @ 8% O_2)

Metal	Inlet	Outlet	Removal
Zinc	77,000–108,000	5–10	96 → 99.99
Cadmium	1000–3500	1.0–0.6	96 → 99.96
Lead	34,000–44,000	1–6	95 → 99.98
Chromium	1400–3100	0.2–1	> 99.92
Nickel	700–2500	0.4–2	> 99.81
Arsenic	80–150	0.02–0.07	> 99.95
Antimony	800–2200	0.2–0.6	> 99.92
Mercury	190–480	10–610	0 → 90

Source: From Carlsson, K. 1986. *Waste Management & Research*, 4; Hay, D. J., Finkelstein, A., Klicius, R. (Environment Canada), and Marenlette, L. (Flakt Canada, Ltd.). 1986. *The National Incinerator Testing and Evaluation Program: An Assessment of (A) Two-Stage Incineration (B) Pilot Scale Emission Control*, Report EPS 3/UP/2, September.

The newest mass-burn facilities seem capable of achieving high reliability, based on their performance in Europe, Japan, and the United States.

Refuse-derived fuel (RDF) facilities became popular during the 1970s. The early plants were generally designed with the intent to remove and recycle metals, glass, and other marketable materials, with the remaining fraction, RDF, to be burned in an existing boiler as a replacement fuel. Those types of facilities all failed and are no longer in operation. The main reasons for failure were that the recycled materials were highly contaminated with waste and were not marketable, and the boilers were not designed to handle the inconsistent RDF that was being fed to them.

The RDF approach quickly evolved to produce a fuel with a known specification to be burned in a dedicated boiler designed specifically to burn that fuel. The materials which were removed were sold, if possible, or landfilled. The primary difference in philosophy between the two types of RDF plants was that the early ones treated the RDF as the “waste” that contaminated the recovered materials, and the newer generation treated the recovered materials as the “waste” that contaminated the RDF. The newer generation RDF facilities which were designed in this manner have been successful.

Fluidized bed technology has been used outside the U.S. to combust solid waste for several years. One advantage of fluidized bed combustion is that the boiler is more efficient than those in mass-burn or spreader-stoker facilities. Also, fluidized bed combustion produces lower NO_x emissions than other incineration methods. Although lower, these NO_x emissions must still be controlled with additional air pollution control equipment, as with other combustion facilities. Fluidized bed combustion also has the advantage of being able to add limestone with the sand in the bed to assist in acid gas removal. However, a scrubber is still needed to reduce emissions to permitted levels.

The major disadvantage to a fluidized bed facility is that it does not have a long-term proven track record in the U.S. Also, the size of the units are small when compared to the size needed for typical U.S. waste-to-energy facilities.

24.6 Costs

It is extremely difficult to obtain accurate, consistent, and comparable WTE plant construction cost data from which to develop information which might be useful in predicting a planned new plant's construction cost during the study stage of a project. However, a 1988 study⁵⁶ has developed such data (appropriate for the time frame of mid-1987), which is confirmed in general by this author's personal experience. This study indicates that for the upper 90% confidence limit for the smallest facility, and the largest facility, the construction costs would range as indicated below:

1. A small modular combustion unit with a waste heat boiler and a capacity of less than 250 TPD—\$68,000 and \$40,000 per ton of daily MSW processing capability. (In most instances, such plants

don't incorporate the same degree of equipment redundancy, and/or the same quality of equipment as the larger plants.)

2. A small refractory wall furnace with waste heat boiler and dry scrubbers of between 200 and 500 TPD capacity—\$90,000 and \$70,000 per ton of daily MSW processing capability.
3. A small, field erected, water wall congeneration or electric generation facility with dry scrubbers of between 500 and 1,500 TPD capacity—\$112,000 and \$85,000 per ton of daily MSW processing capability.
4. A large, field erected, water wall congeneration or electric generation facility with a dry scrubber between 2,000 and 3,000 TPD capacity—\$129,000 and \$112,000 per ton of daily MSW processing capacity.

In this study,⁵⁶ the construction costs were said to include the vendor quote for construction plus contingency, utility interconnection expenses, and any identified allowances clearly associated with the construction price. All other costs, such as land acquisition, interest during construction, development costs, and management fees were not considered or included, where known, due to their highly project specific nature.

The following specific observations were made by the authors at the conclusion of this study.⁵⁶

1. Capital construction price decreases with increasing size within size ranges and increases with a higher-value energy product.
2. Price is also affected by the construction, procurement, and air pollution control methods employed.
3. Refuse-derived fuel and mass burning water wall facilities are competitively priced with each other.

The effect of plant capacity on capital costs or mass-burn plants is shown in Figure 24.8. Capital costs for other types of plants are similar.

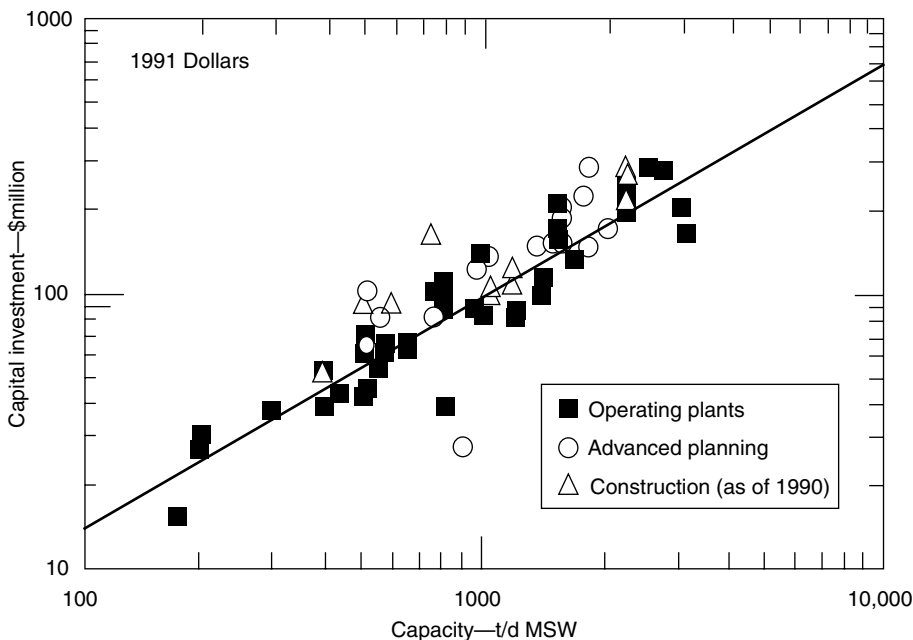


FIGURE 24.8 Effect of plant capacity on capital costs for mass-burn facilities (electricity only), excluding costs associated with collection (e.g., trucks).

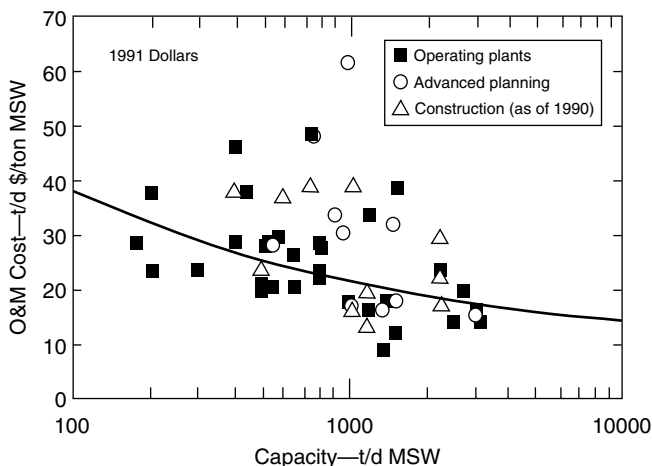


FIGURE 24.9 Effect of plant capacity on O&M costs for mass-burn facilities (electricity producing only), excluding costs associated with collection (e.g., trucks).

With respect to operating costs and/or tipping fees, information is even more difficult to obtain from which to develop costs for planning purposes. Costs cited in the literature from 1989 through 1994 range from \$40 to \$80 per ton of daily rated MSW processing capability.^{20,45,48,78,79} Tipping fees on Long Island, which has generally high labor rates, high power costs, and very long hauls for residue disposal, have been noted to range up to \$110 per ton of daily rated MSW processing capability.²⁸ Plants in other parts of the country where plant operating cost elements are significantly lower have been found to have tipping fees closer to \$40 per ton.⁹ Thus, tipping fees for a specific facility would have to be developed based on cost factors for that specific plant.

The effect of plant capacity on O&M costs for mass-burn plants is shown in Figure 24.9. Information is so limited on other types of plants, and the costs are so dependent on local conditions that we do not feel that curves developed for other types of plants would be useful.

24.7 Status of Other Technologies

Several other technologies have been used to a small extent to burn MSW and beneficially use the energy produced in the combustion process. Their use in the future depends on numerous factors, perhaps the most important of which is full-scale demonstration of successful, reliable operation, after which total operational costs are shown to be competitive with mass-burn and/or RDF combustion costs.

24.7.1 Modular Systems

Modular systems, generally utilized in smaller plants, are assemblies of factory-prefabricated major components joined together in the field to form a total operational system. They have been built in individual unit sizes up to just over 100 tons per day capacity, combined into plants of just over 400 tons per day capacity. Modular systems are similar to mass-burn systems in that they combust unprocessed MSW, but they feature two combustion chambers, and the MSW is charged into the system with a hydraulic ram and combustion takes place on a series of stationary hearths. MSW is pushed from one hearth to the next by hydraulic rams. Two types of modular systems have been built and operated: starved air and excess air.

The primary chamber of a starved air modular system is usually operated in a slightly oxygen-deficient (“starved air”) environment. The volatile portion of the MSW is vaporized in this chamber and the resulting gases flow into the secondary chamber. The secondary chamber operates in an excess air condition, and combustion of the gases driven off the MSW is essentially completed in this chamber. An excess air modular system operates in a manner similar to a field erected boiler system, with excess air injected into the primary chamber.

One advantage of these units, as indicated in the section on costs, is low cost. Another advantage is that factory prefabrication of major system components can result in shortening of the field construction time. One disadvantage of the two-chamber modular system is that waste burn out in the residue is not always complete, which increases ash quantities and reduces the efficiency of energy recovery.⁷⁰ Energy recovery efficiency is also reduced due to generally higher “excess air” levels carried in these units. Also, combustion control is generally less effective in this type of unit, increasing the possibility of discharge of trace organic emissions. As pointed out earlier, these types of units generally utilize a lower quality of equipment and include less redundancy than larger mass-fired water wall and RDF WTE plants. Modular plants are responsible for about 2% of the total MSW burned at this time in the United States.

24.7.2 Fluidized Beds

Fluidized bed combustion (FBC) differs from mass-burn and RDF combustion in that the fuel is burned in “fluid suspension”—entrained along with particles of sand in an upward flow of turbulent air at a temperature controlled to 1500°F–1600°F (816°C–971°C). To date, it has been used primarily to burn sewage sludge, industrial waste, and coal and has been used to combust RDF in one facility in the U.S. Fluidized bed combustion of MSW is more commonly used in some European countries.

“Bubbling” FBC designs retain the material near the bottom of the furnace, while “circulating” designs allow bed material to move upward and then be returned near the bottom of the bed for further combustion. The reason for the interest in this combustion technique to burn RDF is the potential for these designs to provide more consistent combustion because of the extreme turbulence and the proximity of the RDF waste particles to the hot sand particles.⁴⁷ Such systems also require lower combustion temperatures than mass-burn and current RDF systems.

24.7.3 Pyrolysis and Gasification

Pyrolysis is the chemical decomposition of a substance by heat in the absence of oxygen. It generally occurs at relatively low temperatures (900°F–1100°F, compared with 1,800°F for mass-burn). The heterogeneous nature of MSW makes pyrolysis reactions complex and difficult to control. Besides producing larger quantities of solid residues that must be managed for ultimate disposal, pyrolysis produces liquid tar and/or gases that are potentially marketable energy forms. The quality of the fuel products depends on the material fed into the reactor (e.g., moisture, ash, cellulose, trace constituent content) and operating conditions (e.g., temperature and particle size).⁶⁸

Gasification is similar to pyrolysis in that it is the chemical decomposition of the substance by heat in the absence of oxygen. However, gasification occurs at temperatures of approximately 2200°F (1200°C). The reaction produces a synthetic gas with a heat content of approximately 250 BTU/cf. The approximate composition by volume on a dry basis is 25%–42% carbon monoxide, 25%–42% hydrogen, 10%–25% carbon dioxide, and 3%–4% nitrogen and other constituents. The synthetic gas is then cooled rapidly to reduce formation of dioxins and cleaned.⁶²

Several prototype pyrolysis facilities were built in the 1970s with grants from EPA. These facilities were unable to produce quality fuels in substantial quantities. No one in the United States has yet successfully developed and applied the pyrolysis or gasification technology to MSW combustion. However, the use of pyrolysis and gasification for MSW management still attracts attention in other countries. Additional reading for pyrolysis and gasification technologies is available.^{84,85}

24.8 Future Issues and Trends

It has been demonstrated by actual experience that modern mass-burn and RDF-fired MSW WTE plants can be designed and operated with reasonable assurance of continuous service and without adversely affecting nearby neighborhood property values. Allegations that WTE plant sites are situated adjacent to neighborhoods of low-income, disadvantaged, or minority populations ignore the specific technical siting criteria outlined earlier (i.e., adjacent to major highways, low land cost, industrial type area, etc.) which are generally followed in siting such facilities. Such areas frequently are closer to low-income neighborhoods than to middle- and higher-income neighborhoods.⁶⁸

In 1994 the Supreme Court found that a local community could not force the MSW from that community to be taken to a specific facility such as a WTE plant.²⁶ This court decision was a major blow to the WTE industry bringing most planning and construction of new facilities to a halt in the mid-1990s. Many communities, when considering solid waste disposal options, have opted for low cost landfill disposal because of concern over impacts of higher cost WTE alternatives on taxes. At some point in the not too distant future, as the current landfills are rapidly filled, WTE technology will have to be utilized to solve the solid waste disposal problem. Some signs of this new interest in WTE technology are already occurring.

Another issue facing WTE plants is the uncertain future of regulatory requirements, both from the standpoint of legislation and from that of the regulatory agencies. In the past, legislation has been passed by Congress calling for Best Available Control Technology (BACT), then Lowest Achievable Emission Requirements (LAER), and then, most recently, Maximum Achievable Control Technology (MACT). The impact of this legislation, each calling for significant reductions in allowable emissions (absent any indication of the existence of a significant public health problem or benefit), has been to require extensive retrofits of existing plants and addition of equipment to proposed new plants, all at substantial expense without proven benefit and, in many cases, without prior proof of operational viability. Most facilities have opted to upgrade the air pollution control equipment and continue to operate.

Several positive actions are occurring in the field. Thus, most project developers have recognized the desirability of implementing a proactive program early in the project planning process to involve the public, particularly those in the vicinity of the proposed facility.⁶⁰ Also, the potential for materials recycling, which had been overenthusiastically embraced a number of years ago (state recycling goals as high as 70%, with some local communities projecting that their entire quantity of MSW could be managed through recycling), is gradually being recognized.⁴⁶ Franklin Associates²⁵ projects an increase in the recycling rate of from 22% in 1993 to 30% by the year 2000. Much of this increase in recycling is to come from increases in recovery of paper materials and diversion of yard wastes to composting. The impact of these changes in waste composition on energy available at WTE plants will be minimal, with the reduction in moisture content due to diversion of yard wastes being a positive factor.

The need to generate electric energy and safely manage the MSW generated by modern civilization, particularly in the vicinity of major metropolitan areas, together with the proven performance of modern WTE plants, indicate that this technology will be utilized to dispose of a portion of this country's solid waste and provide electricity.

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