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Thermal Processing of Domestic Solid Waste Part 1 of 2 – Combustion Processes

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Thermal Processing of Domestic Solid Wastes
Part 1 of 2 - Combustion Processes

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COURSE CONTENT

This course attempts to answer the question: What is a municipal incinerator? In the early years of refuse incineration in the United States, incinerators were uncomplicated refractory furnaces equipped with metal grates (drawn in most respects from existing coal furnace designs) to move the waste into and through the burning chambers and with (looking back) incredibly simple controls and inefficient air pollution abatement. The furnaces were designed in a technical collaboration between the public works department of the owner city (county, etc.) their consulting engineer and the major component vendors (esp. the grate and/or boiler manufacturer). The 1970's saw the emergence of a new incineration concept: high pressure, waterwall boilers that produced superheated steam that was fed to turbo-generators for power generation (Waste-to-Energy or WTE plants) and equipped with sophisticated process control systems and costly, highly efficient air pollution control. This is the technology that dominates the existing inventory of incineration systems throughout the world.

Such facilities, complex to design and operate, were the product of a new entity: the system vendor. Unlike the earlier situation, the governmental entity with a waste disposal requirement now found themselves in a commercial environment where single-point, overall responsibility for the design and, often, the operation of the facility could be placed in the hands of one of several competing firms. The final working relationship was codified and detailed in a comprehensive contract document (the Service Agreement). The role of the consulting engineer had largely shifted to project planning, assistance in financing, permit submissions and the preparation of performance specifications for competitive bidding by several system vendors. Elsewhere, entrepreneurial system vendors took the lead in developing a project.

The Service Agreement often goes beyond a simple documentation of a contract to provide waste incineration services. Since the lifetime of the Agreement is often 15 to 20 years, many of the circumstances defining the nature of the service, economic factors, environmental requirements and other important parameters will change. Thus, the Agreement not only defines the baseline set of reference system characterizations that were the basis of the original procurement but indicates methods and guidelines with which to update the cost and/or performance basis from the baseline. The characterizations include a “Reference Waste” composition and heat content; unit costs for labor, utilities, taxes and reagents; environmental requirements; and annual processing rates and energy recovery targets.

The new, system vendor-dominated incineration business employs a wide variety of designs to do the same job. This individuality reflects both the growth of incineration technology in recent years and the large number of basic design parameters which are somewhat flexible and can be bent to the prejudices of the design firm. The systems used can be divided into two broad categories: "mass burn technology" that burns raw, substantially unprocessed refuse and "refuse derived fuel" (RDF) technology where a prepared, refuse-based fuel is burned. Although mass burn technology dominates the market in the United States and Europe, both approaches have their strong points and their advocates.

The course begins with a review of the key characteristics of domestic solid waste followed by the options in mass burn incinerator components and system designs and the special characteristics of RDF-based combustion systems. The details of RDF preparation technology is left to other books [1].

A. Introduction

The application of combustion to reduce the volume and sanitize domestic solid waste is an ancient practice beginning with open burning of wastes near villages or other population centers. Modern application of high temperature processes in incinerators (now substantially, WTE systems) have been driven by the growth of population, a community goal of reducing landfilling, increases in per-capita waste generation, the need to increase the capacity and volume reduction for the substantial invested capital and operating expense over earlier designs, and regulatory demands to effectively control the residue and air quality impacts of such operations below acceptable benchmarks of public health impact.

This course assumes a basic understanding of chemistry and mathematics and their application in combustion systems to the level provided in the two-part PDHonline course: *Fundamentals of Combustion*. It presumes basic engineering analysis perspectives but, through text and examples guides the student an understanding of the processes and interactions of combustion-type domestic waste incineration systems. The course includes:

- The basics characteristics of domestic solid waste;
- The design and operating features of components of waste combustion systems (beyond those of Part 2 of the Fundamentals of Combustion course);
- Mass burn incineration; and
- Refuse derived fuel (RDF) incineration.

Part 2 of the course carries the student further into the emerging class of domestic waste thermal processes: Conversion systems which process the waste to an intermediate fuel gas which can then be burned or used as a chemical feedstock.

B. The Characteristics of Domestic Solid Waste

The first step in solving waste management problems is to abandon the hopeless view that “waste” is an indefinite state of matter tied to its genesis as the unusable residue of a process or an unwanted discard of human activity. Instead, waste should be regarded in its own right as a feedstock, a fuel, and/or a potentially useful material. In this new light, the analyst then must seek to determine values for the physical and chemical engineering properties that, though less consistent than those of conventional materials and fossil fuels, nonetheless are the defining measures that characterize behavior.

One must discard the sense that "waste" is so heterogeneous in its composition and variable in its properties that problems with its proper management and use cannot be defined, let alone solved. Waste streams will often exhibit great variability point-to-point and over time. The designer must, therefore, provide processes with more operating flexibility, reserve capacity and materials "stamina" than conventional process equipment. But the development of an estimate of average waste composition and properties along with a sense of the expected excursions from those averages is the necessary starting point of design.

1. Waste Quantities

Table 1 presents the pattern of waste generation and disposition in the United States. Table 2 shows year-to-year averages of waste composition using the EPA method described in Ref. 2. Over this time period the quantity of waste discarded approximately doubled (from 82 to 166 million tons) reflecting a substantial increase in the quantity

Table 1 Patterns of Waste Generation/Management in the United States 1960 to 2007 [2,3]

(kilograms per person per day)

Activity	1960	1970	1980	1990	2000	2003	2004	2005	2007
Generation	1.22	1.47	1.66	2.04	2.10	2.05	2.09	2.06	2.10
Recovery for recycling	0.08	0.10	0.16	0.29	0.47	0.48	0.49	0.49	0.52
Recovery for composting*	Neg.	Neg.	Neg.	0.04	0.15	0.16	0.17	0.17	0.18
Total materials recovery	0.08	0.10	0.16	0.33	0.61	0.64	0.66	0.66	0.70
Combustion with energy recovery†	0.00	0.00	0.03	0.29	0.30	0.29	0.29	0.28	0.26
Discards to Landfill, other disposal ‡	1.14	1.37	1.47	1.42	1.19	1.13	1.14	1.12	1.14
Population (millions)	179,979	203,984	227,255	249,907	281,422	290,850	293,660	296,410	301,621

*** Composting of yard trimmings, food scraps and other MSW organic material. Does not include backyard composting.**

† Includes combustion of MSW in mass burn or RDF form and combustion with energy recovery of source-separated materials in MSW.

‡ Discards after recovery less combustion w/ energy recovery. Discards include combustion w/o energy recovery.

Table 2 Materials Discarded* in the United States 1960 to 2005 [2]

	Percent of Total Discards in United States							
Materials	**1960**	**1970**	**1980**	**1990**	**2000**	**2003**	**2004**	**2005**
Paper and Paperboard	30.2	33.2	31.7	30.5	29.8	26.0	26.9	25.2
Glass	8.0	11.1	10.5	6.1	5.8	5.9	5.9	6.0
Metals								
Ferrous	12.4	10.8	8.9	6.1	5.3	5.4	5.2	5.3
Aluminum	0.4	0.7	1.0	1.0	1.4	1.5	1.5	1.5
Other Non-ferrous	0.2	0.3	0.5	0.2	0.3	0.3	0.3	0.3
Total Metals	13.1	11.8	10.4	7.3	6.9	7.2	7.0	7.1
Plastics	0.5	2.6	5.0	9.7	14.2	15.8	16.2	16.4
Rubber and Leather	1.8	2.4	3.0	3.2	3.4	3.5	3.3	3.4
Textiles	2.1	1.8	1.7	3.0	4.8	5.5	5.4	5.7
Wood	3.7	3.3	5.1	7.0	7.0	7.4	7.4	7.6
Other**	0.1	0.4	1.5	1.5	1.9	2.0	2.0	2.0
Total Materials in Products	59.5	66.6	68.9	68.3	73.8	73.3	74.1	73.4
Other Wastes								
Food Scraps	14.8	11.3	9.5	12.1	15.3	16.6	16.7	17.1
Yard Trimmings	24.2	20.5	20.1	17.9	8.8	7.9	7.1	7.3
Miscellaneous Inorganic	1.6	1.6	1.6	1.7	2.1	2.2	2.2	2.2
Total Other Wastes	40.6	33.4	31.2	31.7	26.2	26.7	26.0	26.6
Total MSW Discarded %	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*** Discards after materials and compost recovery (does not include construction/demolition debris, industrial process wastes)**

**** Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers**

quantity of waste generated and increases in the fraction of the waste diverted from incineration or landfill by composting and materials recovery. Reference 1 includes a much more detailed description of waste quantities and distribution among categories including seasonal and geographic factors.

2. Waste Properties

a. General

Desired data are often lacking to precisely define the design basis for waste processing systems. Many waste studies have demonstrated the large errors possible from desk-top estimates of the generation rate, composition, or properties of waste. It is strongly recommended, therefore, that especially commissioned waste surveys and analyses should be incorporated into the problem definition phase of the design effort. Careful consideration should also be given to the range of variation in composition. For municipal waste, seasonal changes in yard waste content and local precipitation patterns lead to day-to-day fluctuations in moisture content. Economic class, geographical region, culinary preferences and residential styles (homes, apartments, hotels and campgrounds) are significant. In industry, seasonal shifts in production patterns or periodic house-keeping activity lead to variation. Such changes in waste characteristics must be provided for in the design and operating protocols of waste processing systems. Even with such relatively obvious foresight, however, the worst (live ammunition, cans of flammable solvent, containers of toxic chemical, etc.) should be anticipated.

The cardinal rule in waste management design is to ask, "*What happens when...?*" rather than "*What if...?*"

Although the analysis of the specific wastes to be processed is desirable, it is useful to have some general data for preliminary screening of concepts.

b. Composition

Most incinerated material falls within the class "solid waste." Unfortunately, this class of wastes is very difficult to deal with as an "engineering material". Securing a representative sample is often most problematical. Materials handling is difficult and can expose workers to risk. Blending is slow and incomplete. However, for incinerator analysis and design purposes, even highly heterogeneous solid wastes can usefully be considered as a relatively discrete "material" with acceptably reproducible properties and characteristics. Clearly, a somewhat long averaging time may be needed before this constancy is apparent. The data and correlations given below are an attempt to summarize useful information regarding the characteristics of several classes of solid wastes. As with other information in the waste management engineering field, one must recognize that significant excursions from these mean values are to be expected.

Composition refers to the category of material (paper, glass, etc.) in the waste streams. Composition data are reported in this form since the "analysis method," (visual categorization) is low-cost and can rapidly and economically be applied to large samples of waste. This latter point is important if a meaningful characterization is to be made on a stream which is grossly heterogeneous. Data in categorical form may be translated into mean overall chemical compositions and the like by taking the weighted average of the chemical compositions of specified components. Also, data on a categorical basis are directly usable to estimate the potential for materials recovery.

In many instances, the waste stream of interest cannot be directly sampled. Under such circumstances, data from other municipalities can be useful as an indicator of mean refuse composition. Alternatively, the United States EPA settled on an alternate, non-sampling methodology for waste estimation [2]. The EPA method began with a comprehensive estimate (based on published data from both the U.S. Department of Commerce and industry associations) of the domestic production of materials and products including the non-recovered scrap generated in the course of production. Adjustments were then made for imports/exports and diversions to end-uses outside the waste stream (e.g., components used for building materials or toilet tissue that is disposed outside conventional solid waste management systems). Consideration was then given to product lifetime and discounts made for material recovery (resource recovery and composting). The net remaining comprised the waste flow that was discarded to energy recovery or landfill.

Generally, municipal refuse is categorized as shown in Table 3. If, however, a representative sample of waste is separated into these categories and the results tabulated on a weight percent basis, it is found that components that were originally dry (e.g. newsprint) has picked up moisture from wet components (e.g. food waste) which distorts the composition distribution as it might be used to estimate heating value, recycling potential etc. The results are more useful if the moisture levels of the components are adjusted, category by category, to a moisture basis corresponding to the consistent, manufactured state of the materials entering the refuse storage bunker. That involves changing from a mixed or "as-fired" basis characterizing the moisture found in, say, the storage bunker of an incineration system, to the "as-discarded" basis that characterizes the materials as they are produced and with a reference moisture content, basic combustion chemistry and heat content. The moisture content values in Table 4 can be used to effect this basis shift. An Excel© data analysis spreadsheet included in the CD packaged with Ref. 1 is useful in making this adjustment between as-fired and as-discarded bases.

Table 3 Primary Constituents of Mixed Municipal Refuse Categories

Category	Description
Glass	Bottles (primarily)
Metal	Cans, wire, and foil
Paper	Various types (newsprint, office, cardboard and corrugated etc.)
Leather, Rubber	Shoes, tires, toys, etc.
Textiles	Cellulosic, protein, woven and felted synthetics
Wood	Wooden packaging, furniture, logs, twigs
Food Waste	Garbage
Yard Waste	Grass, brush, shrub trimmings
Misc.	Inorganic ash, stones, ceramic, dust

Table 4 Estimated Percent Moisture in Refuse Components [4]

Category	As-fired % moisture	As-discarded % moisture
Glass	3.0	2.0
Metal	6.6	2.0
Paper	24.3	8.0
Leather, Rubber	13.8	2.0
Textiles	23.8	10.0
Wood	15.4	15.0
Food Waste	63.6	70.0
Yard Waste	37.9	55.3
Misc.	3.0	2.0

Carrying out the moisture adjustment [4] can be made using a successive series of assumptions that do not materially change the total moisture content of the total refuse mix, only the distribution of moisture among the refuse categories. Such basis adjustments can become critical for wastes where a substantial fraction of the waste is very moist and, thus, where profound effects of moisture transfer occur.

c. Chemistry

The importance of the chemical composition of a waste is generally greater for sludge/solid wastes than for liquids and much more so than for gases. This generalization derives from the usually large fraction of non-combustible inorganic constituents in solid wastes and the frequently important impact of these elements on system design. The presence of toxic elements and compounds also is important through the resulting impact on worker safety, combustion system efficiency requirements, and air pollution.

Carbon (C), *hydrogen* (H) *and oxygen* (O) are clearly important as the primary elements constituting the fuel fraction of a waste. From data on CHO alone, most of the contribution to the heating value may be estimated.

Nitrogen is modestly important as it appears in fuel value calculations but can be significant as it affects the generation of NO_x air pollution (via the "fuel nitrogen" mechanism).

Sulfur in the waste as the element, and that appearing in organic sulfur compounds or inorganic sulfides is important as results in the generation of the acid gases SO_2 and SO_3 during incineration which impacts on air pollution and corrosion. Sulfate sulfur (for example, in $CaSO_4$ {gypsum} wallboard) remains in the ash.

Halogen content as organic fluorine or chlorine compounds that generate hydrofluoric or hydrochloric acids (HF, HCl) as combustion products are important through their air pollution and boiler corrosion consequences. Bromine and iodine compounds are also significant in these regards but their combustion chemistry and frequency of appearance differ markedly from the F/Cl case. Note that the high temperature corrosion caused by inorganic chlorides in the ash layer on boiler tubes has been observed to decrease as the sulfur content of the waste increases.

Phosphorous can be important primarily as it affects the melting point of residues and slag deposits. Burning organophosphate pesticides produces phosphorous pentoxide (P_2O_5) that significantly depresses the slag fusion temperature. Some inorganic phosphates (e.g. $FePO_4$) also depress the ash melting point.

Potassium and sodium content are important as they may indicate the presence of low-melting compounds (e.g., NaCl, Na_2SO_4) which affect slag fusion temperature. The sodium chloride - sulfate eutectic is particularly troublesome in burning refinery and petrochemical sludge. Also, fused alkali metal compounds often penetrate porous refractory followed by spalling when the refractory cools.

Toxic organic compounds are clearly important as they impact on worker safety and on the requirement for effective combustion and combustion control. Stack emission of many specific organic compounds that have demonstrable health effects at low concentrations (e.g., benzene and vinyl chloride monomer) is limited in many countries by the air pollution regulations.

Heavy metals and other toxic elements (esp. Cd, Hg, Pb, Zn, Cr, Cu, Be, As, Se, Ni, Ag) are important since combustion will not destroy them: they will appear in the residue and in the fly ash thus, perhaps, rendering the residues subject to the hazardous waste regulations with consequent ballooning of the cost, liability and administrative complexity of residue disposal. Toxic elements with compounds that volatilize at combustion temperatures (esp. the chlorides and some oxides of Cd, Hg, Pb, Zn, As, Se and Ag) are of interest since they will often be emitted from the stack as a sub-micron particulate and will deposit on other finely divided particulate. Most data indicate a significant “enrichment” of these elements in the fine particulate matter compared to that in the total ash in the raw waste.

Chemical data for many refuse constituents are shown in Table 5.

Table 5. Composition and Chemistry of Municipal and Commercial Solid Waste Components

	As Discarded	Dry Basis Elemental Composition							
Component	**Moisture**	**C**	**H**	**O**	**N**	**S**	**Cl**	**Ash**	**Dry HHV**
Paper, Mixed	10.24	43.41	5.82	44.32	0.25	0.02	0.00	6.00	4,207
Newsprint	5.97	49.14	6.10	43.03	0.05	0.16	0.00	1.52	4,711
Brown Paper	5.83	44.90	6.08	47.34	0.00	0.11		1.07	4,281
Corrugated Boxes	5.20	43.73	5.70	44.93	0.09	0.21		5.34	4,127
Plastic-Coated Paper	4.71	45.30	6.17	45.50	0.18	0.08		2.77	4,279
Junk Mail	4.56	37.87	5.41	42.74	0.17	0.09		13.72	3,543
Vegetable Food Waste	78.29	49.06	6.62	37.55	1.68	0.02	0.00	4.89	4,594
Fried Fats	0.00	73.14	11.54	14.82	0.43	0.07		0.00	9,148
Mixed Garbage	72.00	44.99	6.43	28.76	3.30	0.52	0.00	16.00	4,713
Green Logs	50.00	50.12	6.40	42.26	0.14	0.08	0.00	1.00	2,336
Demolition Softwood	7.70	51.00	6.10	41.80	0.10	0.05		0.80	4,398
Furniture Wood	6.00	49.70	6.10	42.60	0.10	0.05		1.40	4,341
Evergreen Shrubs	69.00	48.51	6.54	40.44	1.71	0.19		2.61	4,853
Lawn Grass	75.24	46.18	6.61	36.43	4.46	0.42		6.55	4,618
Brush	40.00	42.52	5.90	41.20	2.00	0.05		8.33	4,389
Upholstery	6.90	47.10	6.10	43.60	0.30	0.10	0.00	2.80	4,155
Tires	1.02	79.10	6.80	5.90	0.10	1.50		6.60	7,726
Leather	10.00	60.00	8.00	11.50	10.00	0.40		10.10	4,917
Leather Shoe	7.46	42.01	5.32	22.83	5.98	1.00		22.86	4,348
Shoe, Heel & Sole	1.15	53.22	7.09	7.76	0.50	1.34		30.09	6,126
Rubber	1.20	77.65	10.35	0.00	0.00	2.00		10.00	6,294
Polyethylene	0.20	84.54	14.18	0.00	0.06	0.03		1.19	10,961
Polystyrene	0.20	87.10	8.45	3.96	0.21	0.02		0.45	9,139
Polyurethane	0.20	63.27	6.26	17.65	5.99	0.02	2.42	4.38	6,236
Polyvinyl Chloride	0.20	45.14	5.61	1.56	0.08	0.14	45.41	2.06	5,431
Linoleum	2.10	48.06	5.34	18.70	0.10	0.40		27.40	4,617
Rags	10.00	55.00	6.60	31.20	4.12	0.13		2.45	4,251
Oils, Paints	0.00	66.85	9.63	5.20	2.00	0.00		16.30	7,444

d. Heat of Combustion

In the analysis and design of incineration systems, few waste parameters are as important as the heat of combustion. The correlations and estimation tools supplied in Part 1 of the Combustion Fundamentals course are more tailored to the waste incineration field and, in some cases, may be more easily applied.

e. Materials Handling

Probably no single element of incineration systems causes more problems than those related to the handling of wastes. One of the most significant differences between liquid and gaseous waste incineration systems and those for sludge and solids concern the equipment used to collect, transport, store, reclaim and fire the wastes. In many cases, weaknesses or failures in the design of materials handling subsystems have greatly reduced the utility and increased the O&M problems and costs of solid or sludge waste management facilities.

The angle of maximum inclination differs from the angle of repose (Table 6) which measures the angle between the horizontal and a sloping line from the top of the pile to the base. It was noted [5] that waste materials seldom form conical piles so several "angles of repose" appear in a given pile. For densified RDF (d-RDF), the angle varied as the pellets broke down. Loose, degraded pellets produced higher angles than hard, stable pellets. The angle of surcharge is similar to the angle of repose: the angle to the horizontal which the surface of the material assumes while at rest on a moving conveyor belt.

The angle of slide (Table 6) is that angle to the horizontal of an inclined flat surface on which an amount of material will begin to slide downward due to its own weight: an important parameter in design of chutes or diverters. The data in the table show the effects of the type and condition of the underlying surface. The state of compaction and rate of change of tilt in the measurement process also affect the results. The loose bulk density and the bulk density after vibration for consolidation (Table 7) are other important properties.

Table 6 Materials Handling Properties
(all angles in degrees) [5]

Solid Waste Fraction	**Angle of Repose**		**Angle of Slide**		**Angle of Surcharge**		**CEMA Code** [a]
	Range	**Ave.**	**Steel Plate**	**Conveyor Belting**	**20 ° Idler**	**35 ° Idler**	
MSW	25 – 52	39	29.3	30.0	55	54	E36HJVO
RDF	29 – 49	40	31.0	35.0	51	65	E35HJLXY
d-RDF	27 – 46	38	32.8	34.5	N/A	49	$D_3$35HJQL
Heavy fraction	30 – 59	40	27.5	28.5	48	59	E47HQVO
Ferrous fraction	N/A	N/A	N/A	N/A	N/A	52	D_{16}6
d-RDF/Coal 1:1 (vol.)	40 - 50	42	22.0	24.0	N/A	40*	$D_3$45HJQL

* This data point is of uncertain accuracy

[a] Conveying Equipment Manufacturers Association.

Table 7 Bulk Density (kg/m^3) [5]

Solid Waste Fraction	Loose Range	Loose Ave.	Maximum Range	Maximum Ave.
MSW	61-152	66	66-200	134
RDF	34-50	43	37-72	54
d-RDF	361-387	374	402-486	445
Heavy fraction	366-598	482	334-451	435
Ferrous fraction	N/A	N/A	194	194
d-RDF/Coal (1:1 (vol.)	712	712	590	590

C. Incineration Systems for Municipal Solid Waste (MSW)

1. Performance Objectives

The performance objectives of a municipal waste incineration system are:

- To process each normal operating day not less than the quantity of waste with an analysis and heat content equivalent to that specified in the Service Agreement.
- To process the minimum weekly, monthly and/or yearly quantity of waste equivalent to that specified in the Service Agreement.
- To consistently operate within the emission limits and other legal constraints of all applicable environmental regulations to include restrictions on the concentrations or mass rates of air or water pollutants, sound pressure levels, and/or the maintenance of specified system operating parameters within designated limits.
- To protect the health and well-being of incinerator employees and of the commercial and residential community that abuts the operation.
- To protect the capital investment reflected in the equipment, buildings, roads etc. comprising the incineration facility such that the useful operating life and maintenance and operating expenses of the incinerator are not adversely impacted.
- To meet any production guarantees regarding residue quality and quantity; export rates of power, steam or other energy-related products; or other commercial promises.

The achievement of these objectives is strongly supportive of a healthy plant operation, good customer relations and good financial performance.

a. Throughput and Refuse Heat Content

Many of these performance objectives are strongly influenced by the characteristics of the waste. The most basic connection is through the heat content of the waste material since, in essence, an incinerator is a system to process heat. Therefore, the capacity of an incinerator is intrinsically associated with a maximum heat release rate (the Maximum Continuous Rating or MCR) and not a mass throughput rate (except as the mass rate, multiplied by the waste heat content, is equivalent to a heat release rate). Unfortunately, many municipal clients believe that their contract relationship with the incinerator operator is a commitment to process a given mass of material (e.g., 400 tons per day) rather than to process a specified number of millions of kilocalories per day. If this potential misperception is not clearly addressed in the Service Agreement, changes in waste heat content over the contract life will lead to customer dissatisfaction and, even, lawsuits.

Why is heat release the "real variable?" Figure 1 illustrates the process and hardware connections that spring from the MCR heat release parameter. Heat release rate, because of the approximate equivalence between heat release and combustion air quantity, is strongly related to the volumetric flow rate of combustion air and of the products of combustion. Thus, the heat release rate sets the size of the forced draft and induced draft fans; sets the size of the air pollution control system and sizes the ductwork, dampers, pressure drops etc. throughout the flow system. Also, the heat release rate, for a given combustion chamber, strongly impacts on the heat transfer rates (both convective and radiative) which affects the temperature of surfaces in boilers and on refractory walls. Thus, exceeding the design heat release rate can result in overheating of critical system components. All of these factors illustrate why incinerator capacity is quite properly equated to the MCR rather than the tons fed.

Another limitation on capacity relates to the structural strength and materials handling capabilities of the grate and the physical dimensions and capacity of the residue and fly ash handling systems. These physical limitations generally limit the furnace throughput to approximately 110% of the basic design capacity.

b. The Firing Diagram: The Overall Process Envelope

The firing diagram shown in Fig. 2 provides a concise, graphical statement of the operating process envelope of an incineration system. Specifically, the area bounded by the dotted lines represents the combinations of mass feed rate and refuse heat content that are supported by the referenced incineration furnace. For all points within the dotted area, the furnace can meet its design mass disposal rate and still remain at a technically sound fraction of MCR and the physical throughput limitations.

Let us consider the various elements of the boundary of the operating zone:

Maximum heat release **–** The horizontal "top line" of the zone is the MCR. Heat release rates over this limit unduly stress the equipment or exceed design limits for fans, air pollution control equipment etc. Also, in waterwall boiler systems, operation above this heat release rate may lead to boiler tube failures, tube erosion etc. contributing to unscheduled outage.

50% of MCR **–** The horizontal "bottom line" of the zone is set at 50% of the MCR. While somewhat arbitrary, burning at less than one-half of the design heat release is often accompanied by poor mixing (increasing CO and hydrocarbon pollutant emissions), degradation in residue quality, furnace control problems, draft control problems, etc.

110% of Maximum Throughput **–** The vertical "right-most boundary" of the zone is set at 110% of the design mass throughput. This is a reasonable estimate of the maximum feed rate that can be accommodated by the grate and residue handling systems.

50% of Maximum Throughput **–** The vertical, "left-most boundary" of the zone is set at 50% of the design mass throughput reflecting the constraint that as the throughput drops from the design level, it becomes more likely that the grate will be exposed to furnace radiation. Also, the breakdown in the performance of the solids materials handling equipment becomes more likely.

Maximum Rate of Highest Heat Content Refuse **–** The "sloped top boundary" of the zone is set by the Heat Release - Throughput line for the highest heat content refuse. This line intersects the MCR line at the design throughput line. This is the maximum heat content refuse used as the basis of design in setting the MCR. Note that for this heat content refuse, the system can just meet the design throughput rate (often equal to the minimum rate set in the Service Agreement) and stay within the MCR.

Figure 1 MAXIMUM CONTINUOUS RATING (MCR)

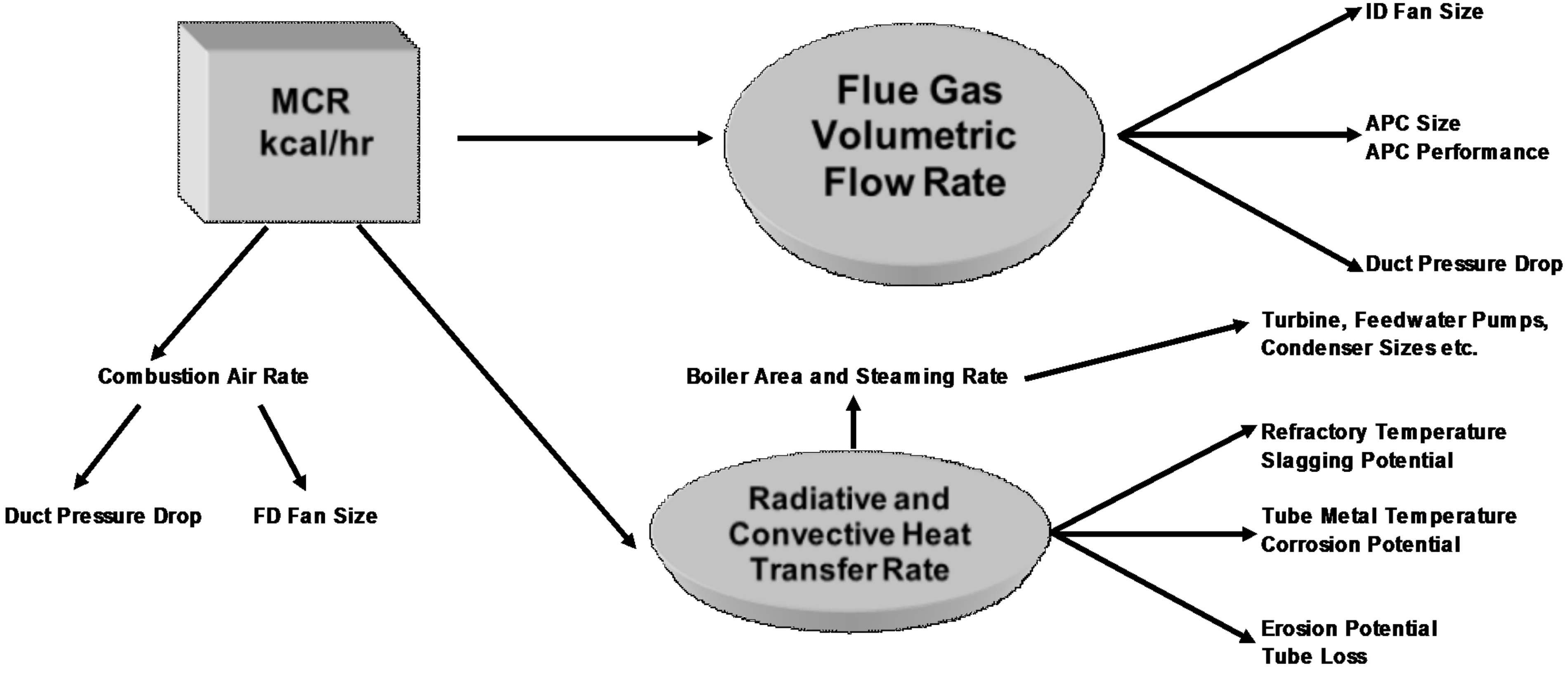
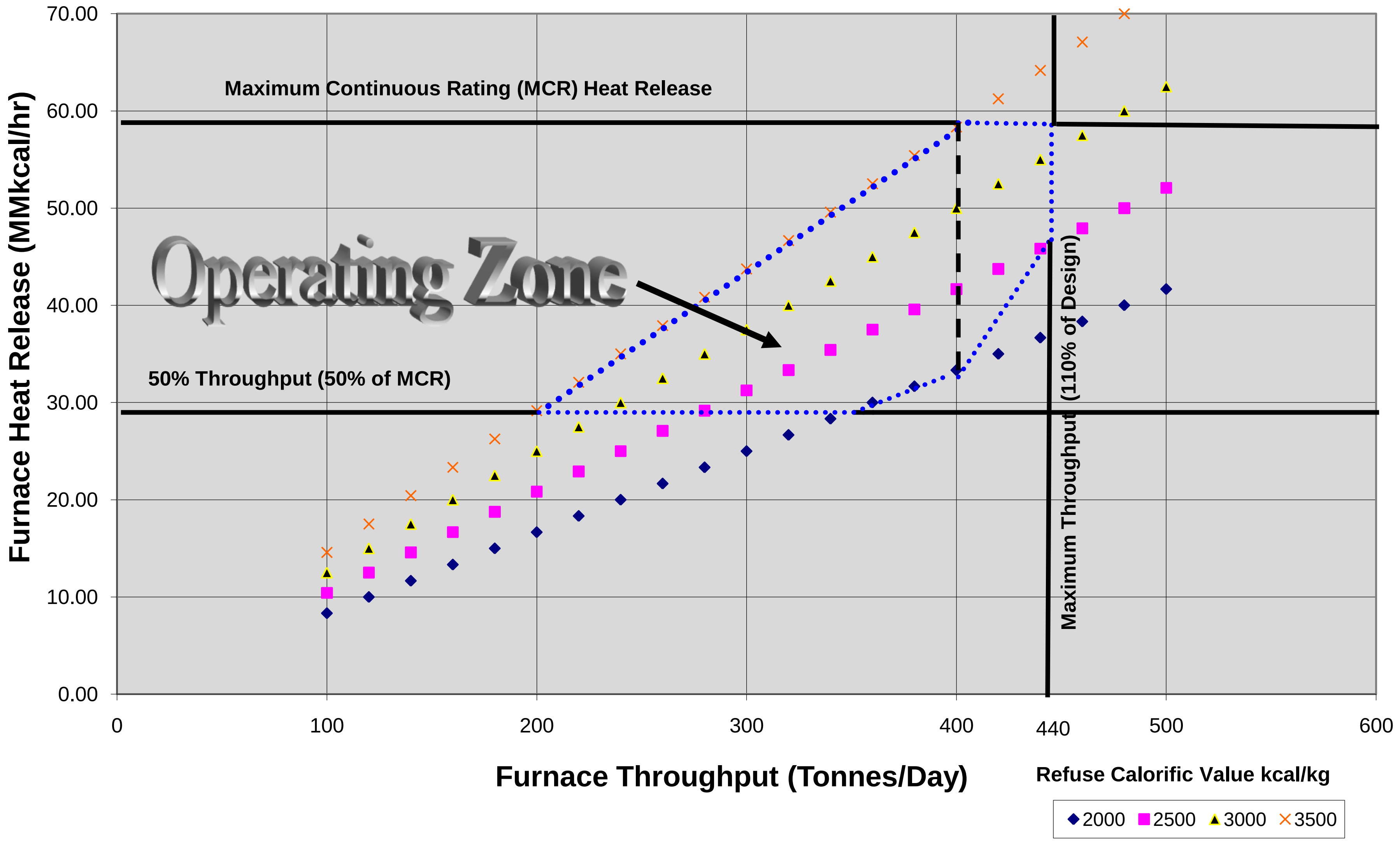


Figure 2 400 TPD Incinerator Firing Diagram



Maximum Rate of Lowest Heat Content Refuse **–** The "Sloped bottom boundary" of the zone is set by the Heat Release - Throughput line for the lowest heat content refuse that intersects the 50% MCR line and extends to the design capacity limit.

Since the Operating Zone described in the Firing Diagram is a simple, graphical statement of the maximum operational capabilities of the incineration system, there are merits to including the Diagram as part of the Service Agreement.

2. Site Design Considerations

The design of the incinerator site impacts significantly on the cost of the facility, the control of storm water run-off, and the efficiency of the truck traffic flow. Site development costs typically represent two to four percent of the total cost of a plant, but can increase if substantial earth moving is required for the site. Storm water must be controlled to limit the impacts of plant runoff on nearby receiving waters (streams, rivers and lakes). Traffic back-ups (queuing) can occur if the plant roadway system is not configured properly. The designer must consider all of these site issues when evaluating different sites for the plant, and in orienting the plant on the selected site.

3. Refuse Storage, Handling and Feeding

In the incinerator system, the handling of refuse begins with the delivery of materials to the site. In the United States most refuse is delivered to the site in motor vehicles. Delivery vehicles can include open dump trucks, commercial vehicles and private cars but most of the waste is conveyed using specialized trucks with equipment for compression and densification. In some instances, very large (50 to 70-m^3) compaction truck trailers are employed to ferry refuse from centrally located transfer stations.

The refuse loaded into the original collection vehicles usually has a density of about 80 to 240 kg/m^3. A power compaction unit can compress the refuse at the generation site (such as at commercial establishments, hospitals, apartments, hotels, etc.) to a density of about 500 to 1000 kg/m^3. However, most refuse loaded into vehicles at the collection site is compacted in the truck body to 250 to 500 kg/m^3. Most incinerators have a scale to weigh the incoming refuse.

Refuse is a perverse material with unusual physical and mechanical properties. Unlike many solids, it does not cone when piled up and often exhibits a negative angle of repose (an overhang). Because of its source and moisture content, portions of the waste can be sticky so it may not discharge cleanly from belt or apron conveyors. This can cause housekeeping problems along the return run. Waste compresses, which can result in binding at points of close tolerance in moving machinery. Since the compressed material is not brittle and thus does not break off, the tough, compressed waste can keep gates and doors from closing fully. Waste comes in a wide range of physical forms (sheets, ribbons, bales, cans and bottles, books, powders, boxes and magazines, food scraps and so on). This variability emphasizes the special need for rugged and flexible materials handling equipment.

a. Tipping Floor-Based Waste Storage and Reclaim Systems

In small incinerator plants (say, less than 150 tons per day), a paved tipping floor is used where the refuse is dumped directly onto the floor by the collection vehicles and marshaled into piles using front end loaders. On demand, waste is reclaimed from the storage piles and charged to the incinerator(s). The tip floor area for the storage piles includes a concrete push-wall so that the pile does not move when a front-end loader picks up a load. Typically, the maximum pile height is 3.5 to 4 meters and typical waste density is 200 to 250 kg/m^3.

The floor-dump approach is low in initial capital cost in comparison to the pit and crane design described below. Also, the floor dump facilitates visual checking of incoming refuse for excluded wastes (e.g., hazardous materials and automobile batteries). However, fire control is difficult.

b. Pit and Crane-Based Waste Storage and Reclaim Systems

In larger incinerator plants, refuse is most often received and stored in a pit below ground level. A traveling crane with an "orange peel grapple" is most often used to pile the refuse for storage and to move it away from the area just below the unloading area so the pit can accommodate additional refuse. (see course notes: Fundamentals of

Combustion Part 2). The crane and bucket are also used to feed the incinerator furnace. Generally, the pit is sized to hold the quantity of refuse that can be burned in 2 to 3 days.

Open receiving areas are possible but they are infrequently used. The receiving area should be enclosed to avoid windblown refuse from causing a nuisance, to control dust and odors, and to prevent rain, snow and ice from wetting the refuse and interfering with the vehicles. Fires in the pit are not uncommon

c. Bin Storage and Reclaim Systems for RDF

Systems to store and retrieve RDF are critical to the operational success of all classes of RDF combustion systems. Because the processed RDF, sitting quiescently in a bin or other storage bunker, has a tendency to “knit” together into a coherent structure, dynamic storage is provided that involves continuous operation of the withdrawal mechanism and continuous recycle of the unfed RDF flow. A second aspect of successful dynamic storage has sometimes involved the installation of vertical screws in the storage bins to continuously “fluff” the RDF. Parallel paired counter-rotating withdrawal screws in the bin bottom provide a “live bottom” feature that also has proven successful but, with continuous movement, the wear problems fostered by the highly abrasive nature of waste, sand and grit is exacerbated and fouling with wires or ribbons is common.

The RDF storage bin is important because, in most instances, the RDF preparation system is only operated on a one- or two-shift basis. The RDF processing capacity is often considerably greater than the needs of the combustion facility. Thus, a facility is needed to hold a relatively large working volume of waste to bridge over the shift outages and maintenance outages of the processing system. Ideally, a surge storage bin is interposed between the long-term storage bin and the combustor. The quantity of material in the surge bin usually corresponds to 5 to 10 minutes of firing at the design rate.

d. Feeding Systems

Hopper feeding using hydraulic rams is conventionally used in small incineration systems (see Solids Feeding in Part 2 of the Combustion Fundamentals Course. In larger, mass-burn incinerators, the grapple is used to feed a chute discharging into the primary combustion chamber as shown in Figure 3.

Feeders for refuse derived fuel (RDF) involve either mechanical vaned spreaders or pneumatic spreaders. An example of the latter is shown in Fig. 4.

4. Grates and Hearths

Small incineration furnaces use a stationary grate or refractory hearth to support the burning refuse. Most of the larger plants use one of several available grate types to support and transport the refuse while simultaneously stoking or mixing the refuse during the combustion process. Suspension burning is the only process that does not necessarily require a hearth or grate, since most of the refuse is oxidized while in suspension in furnace gases. However, a burnout grate is usually installed at the bottom of suspension burning furnaces to achieve more complete burnout of combustibles in the residue and to provide burnout time for oversize. Experience shows that only when the refuse has been shredded to 95% < one centimeter can one consider abandoning the burn-out grate. There are many different types of hearths or grates, each of which has its own special features.

a. Mechanical Grates: Continuous Operations

Mechanical constant-flow grates have been and are being used in most of the newer continuous burning municipal-scale incinerators (see Fig. 3). The constant-flow grate draws refuse from the refuse feed chute into the incinerator furnace, provides movement of the refuse bed and ash residue toward the discharge end of the grate, and does some stoking and mixing of the burning material on the grates. Underfire air passes upward through the grate to provide oxygen for the combustion processes, while at the same time cooling the metal portions of the grate to protect them from oxidation and heat damage. Typical grate designs correspond to an average heat release rate of 13,500 to 16,000 kcal m^{-2} min^{-1}. Clearly, the actual rate in different portions of the grate differs widely from this average.

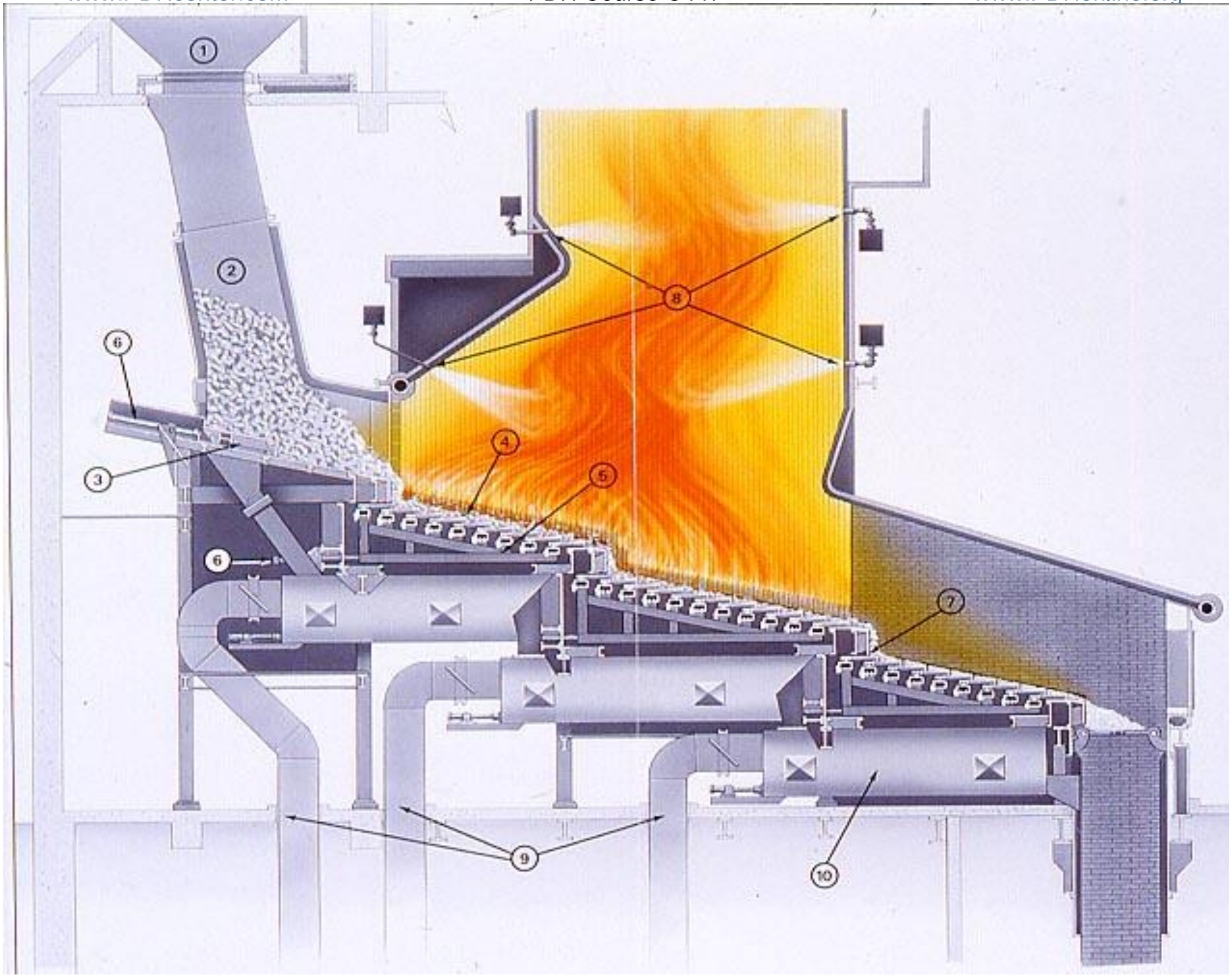


Fig. 3 Detroit Reciprograte stoker (Courtesy of Detroit Stoker Company)

1-refuse charging hopper; 2-refuse charging throat; 3-hydraulic charging ram; 4- grates; 5-tapered roller bearings; 6-hydraulic power cylinders and control valves; 7-vertical dropoff; 8-overfire air gets; 9-undergrate combustion air supply ducts; 10-automatic siftings removal

The grate device is only one part of the overall primary furnace system. The primary furnace system includes the hopper/chute/feeder, the grate and underfire air system, the furnace enclosure with its protective sidewalls, the overfire air system (including design features such as the shape of the lower regions of the enclosure and the direction and discharge velocity of the air jet nozzles), and the bottom ash and siftings equipment. While each vendor makes claims as to the benefits of his particular grate design, most firms have invested considerable time and money in developing an optimized, overall primary furnace system that works together as a successful, integrated package.

RECIPROCATING GRATE– Reciprocating grates (see Fig. 3) involve cast alloy grate bars, actuated in sequence to push, mix and help to break up (stoke) the refuse. Since the early 1970's, the reciprocating grate system has become the most commonly used type in mass burn incinerator service. The plane of the grates provided by the several grate vendor firms throughout the world ranges from flat to inclined downward toward the ash discharge point. Grate bar actuation devices may push toward the ash discharge (the preponderance of grates are of this design) or push “uphill” toward the feed end. Grate cooling is most commonly achieved by the convective exchange of heat to the incoming undergrate air flow v l by steam flow rate measurement to mod

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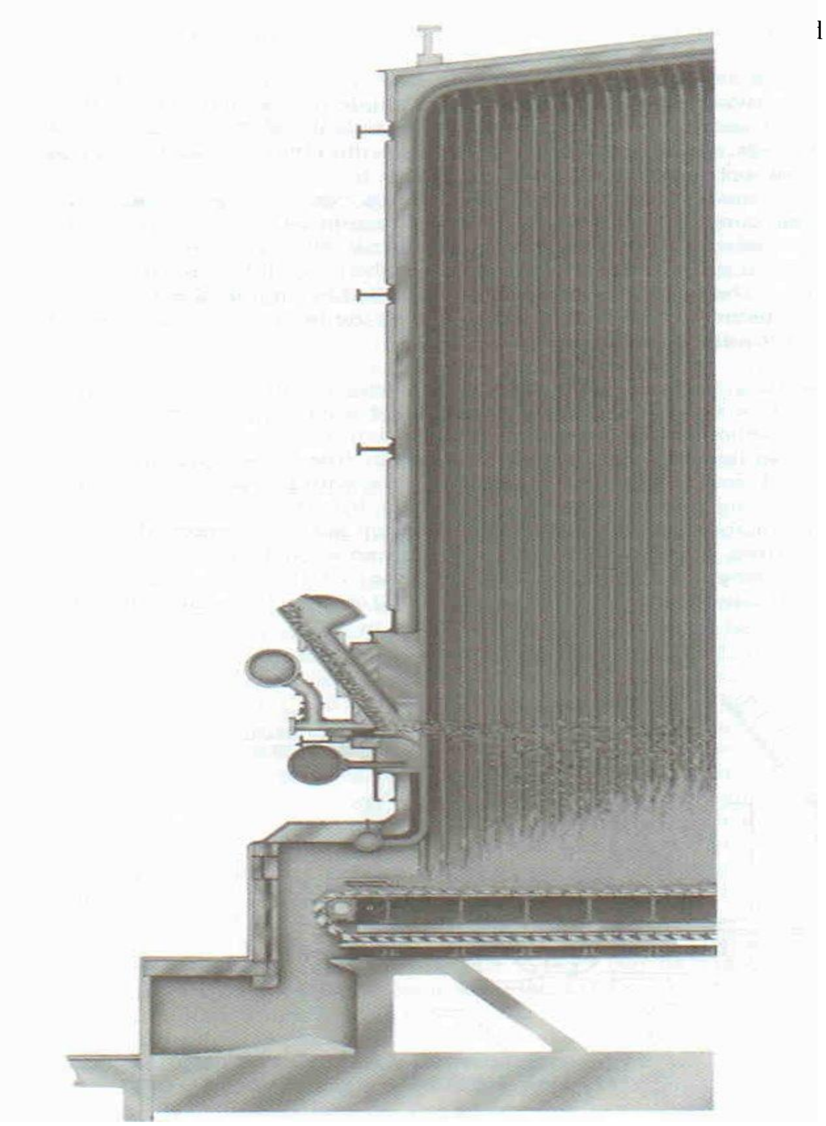

Fig. 4 Pneumatic RDF boiler system (Courtesy Babcock Borsig Power Inc.)

TRAVELING GRATE – The traveling grate (Fig. 5) was the most widely used grate for continuous flow mass burning incinerator furnaces through the early 1970's. It remains the most common alternative in RDF-fired furnaces where there are many installations in the United States, in Europe, and in Japan. The traveling grate has been in use for many years in coal fired furnaces and, as in most grate systems, was adapted for use in municipal incinerators. There are two types of traveling grate stokers: the chain grate and the bar grate. In mass burning designs, the grate conveys refuse from the gravity feed chute through the incinerator furnace to the ash residue discharge, much as a conveyor belt. In RDF applications, grate heat release is approximately two million kcal/m^2-hr, with about 12.8 kcal/hr heat input per meter of grate width over 45 to 50 percent of the grate width. Typical grate speeds approximate 7.6 meters per hour.

b. Fluid Bed Furnaces

The fluidized bed furnace (FB) is an inherently simple combustor. Air at high pressure is forced through a bed of sand. The sand particles become suspended in the rising gas and take on the behavior of a turbulent liquid: bubbling and flowing so as to maintain especially uniform temperatures throughout the bed volume. Typically, gas temperatures vary less than 5 to 8°C between any one location in the bed and another. The gas velocities under these conditions average between 0.7 and 1.0 m/sec.

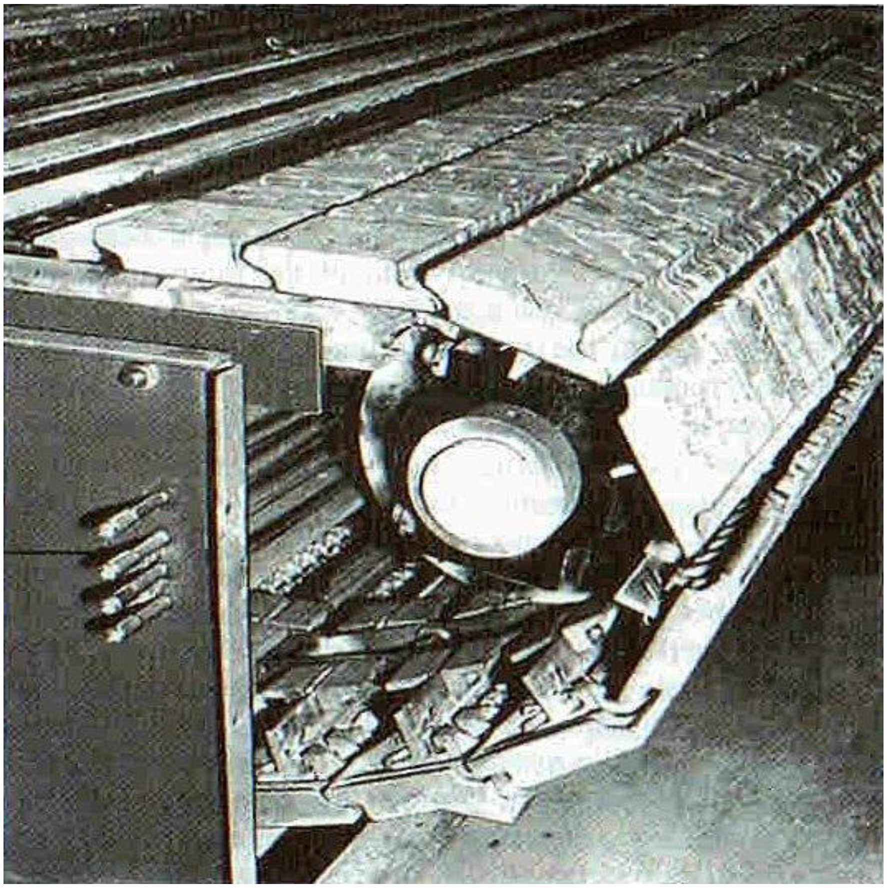

Figure 5 Chain Grate Stoker (Courtesy of Babcock Borsig Power Inc.)

The top of the bed is relatively well-defined and the gas rising through the bed includes clearly defined gas bubbles. The hydraulic behavior of the fluidized bed is as though it held an ordinary liquid: solids with a lower density float; the upper surface is well defined and remains horizontal when the bed is tipped; the surface levels equalize when two chambers are interconnected; solids will overflow if the upper surface is higher than a drain point in the sidewall. This is the conventional, "bubbling fluid bed" (BFB) mode of operation.

Above the fluid bed is large, cylindrical disengaging space known as the freeboard. The freeboard usually provides about 3 to 4 seconds of residence time for final burnout of combustible material. The freeboard operates at or slightly above the bed temperature. The finely divided ash is swept out of the bed and is collected in a scrubber or other air pollution control system. Coarse or heavy particles remain in the bed: decrepitating with time and elutriating or requiring removal through a drain.

At a given time, only a small portion (usually less than one percent) of the bed mass is combustible matter. The large mass of the bed gives it thermal inertia so that the bed can absorb fluctuations in feed characteristics. Solids fed into the bed or into the freeboard are rapidly heated by radiation and intense convection. The rapid heat and mass transfer between bed constituents results in temperature uniformity, with not more than a few degrees Centigrade differential between any two parts of the bed.

In order to provide a feed with relatively homogeneous composition and size, almost all solid wastes fired in BFB units are pre-processed or, at least, made somewhat more homogeneous through waste separation at the point of generation. BFB furnaces can accept other fuels such as wood chips, coal, or chipped tires. By acquiring these relatively clean, alternate energy sources when the prices are favorable, energy revenues can sometimes be increased significantly with little increase in maintenance and operating cost.

Figure 6 shows an embodiment of the BFB used in the United States for MSW (fired as an RDF), wood waste etc. This design illustrates many of the special features required for this application. These include:

Special Residue Drawdown Cones or other specialized means to remove oversize inert material (stones, glass shards, wire etc.) that will not transport out of the reactor. High capacity ash handling equipment is also appended; often with double-deck screens to recycle fines and remove oversize.

Special Pneumatic Feeder Systems to cast the shredded waste (90% < 7.5 cm.) across the bed. Larger beds can accommodate small boxes (as, for example, 5 kg. boxes containing medical waste).

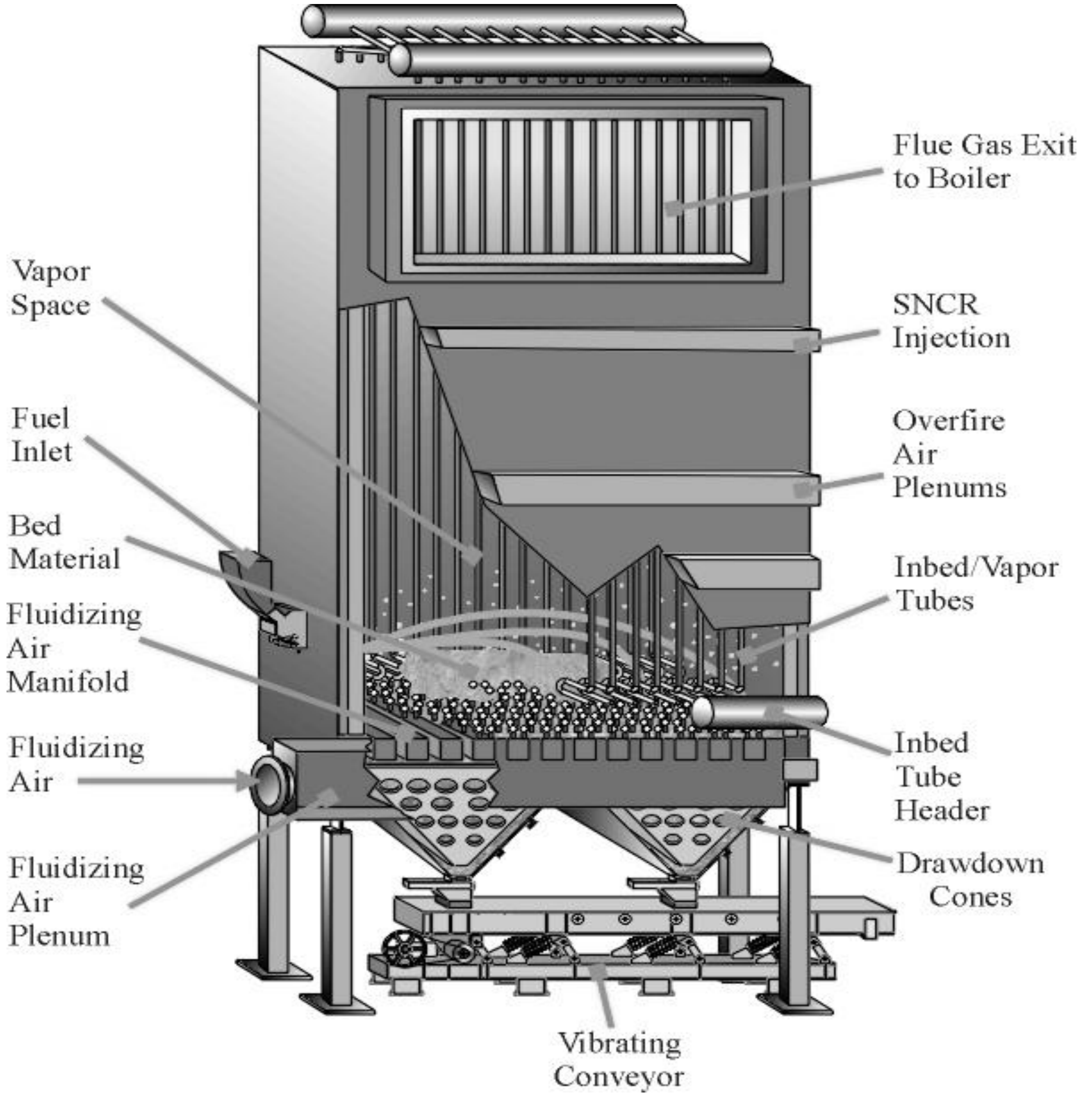

Figure 6. Bubbling Fluidized Bed (Courtesy EPI Inc.)

In-bed/Vapor Tubes to remove heat from the combustion space. The high heat content and low moisture of MSW results in flame temperatures high enough to result in ash fusion and clinker formation unless energy is removed from the flue gases. Therefore, boiler tubes are incorporated into the refractory furnace design. Often, nearly half of the total steam generation occurs in the in-bed tubes.

Selective Non-Catalytic Reduction (SNCR) injection of reagent (such as ammonia or urea solution) to reduce NO_x by reduction to elemental nitrogen.

Overfire Air Injection to enhance mixing and complete the supply of combustion air (typically about 40-50% excess air overall) to assure complete burn-out of char, CO, VOC's and other combustible gases/pollutants. Overall residence time is about 4 seconds; 2.5 seconds after overfire air injection.

5. Enclosures

The furnace enclosure provides a controlled environment for the combustion process in the incinerator system. Without the furnace enclosure, the combustion process would be, in effect, "open burning." Incinerator enclosures (refractories, boiler systems etc.) were discussed in the Combustion Fundamentals (Part 2) course.

Combustion engineers know that a hot, well-mixed system, supplied with sufficient air will achieve complete burnout of even the most refractory organic compounds in only a fraction of a second. For conventional fuels, burner designs can be honed with the combined guidance of experiment and theory (the latter greatly aided by the regularity of the system) to coax out superior combustion performance over wide ranges of operating conditions. The features of the combustion enclosure in this instance are, therefore, more driven by issues of cost, heat transfer optimization and "packaging convenience" than by the combustion process.

In contrast, we know that grate burning is an inherently poor starting point for the realization of complete combustion. The air supply is spatially and temporally irregular as is the air demand. The gasification and heat release processes are in a state of continual upset as the reciprocating grate bars expose new surface and as piles of refuse collapse and fall. This chaos is in stark contrast to the humming regularity of oil, gas and even pulverized coal flames.

In the incinerator, the physical shape of the furnace enclosure and its appurtenances play a key role in achieving incineration objectives. The function of the furnace envelope in refuse fired combustors can be critical; guiding cold, gases from the discharge grate area back to the hotter regions where, after mixing, combustion is initiated; guiding hot gases to energy depleted zones for ignition and drying; guiding oxygen rich gases to the air-starved pyrolysis zone in the second third of the grate.

The furnace shape also serves to funnel and accelerate the fuel-rich gases rising from the gasification regions along the grate to target zones for overfire air jet mixing (see Fig. 3). The walls constrain the flow to maintain gas velocities high enough to overcome buoyancy-driven stratification and to avoid cold spots and dead zones: wasted combustion volume. Also, the furnace shape, facilitated by skillful placement of (hot) refractory can provide re-radiation to the bed: supplying heat energy for the evaporation of moisture.

The achievement of a very high degree of combustible pollutant control in municipal incineration systems over the period 1975 to 1985 (including reliable destruction of the precursors of dioxin and furan compounds) was a remarkable technical achievement of the industry. Intensive studies of furnace shape, overfire air injection design, and combustion controls (coupling combustion environment sensors to refuse feed rates and air supply) combined to accept and meet the challenge of dealing with grate-fired systems burning unprocessed, non-homogeneous waste.

The volumetric heat release rate characterizes the combustion intensity and wall temperature level in the furnace enclosure. Although designs vary, most refractory furnaces fall within the range from 130,000 to 225,000 kcal hr^{-1} m^{-3}, with an average of about 180,000 kcal hr^{-1} m^{-3}.

In most modern incineration systems, energy recovery in a water-walled boiler generating superheated steam (Waste-to-Energy or WTE) is the only economically viable and environmentally sound concept for combustion-based waste processing. With such a concept, the cooling effect of the water-cooled walls allow the excess air to stay low (lowering the flue gas volume and the size and cost for air pollution control, fans and stacks) and the power revenue provides a significant off-set to the high capital investment and operating expense of incineration systems. Typical heat release rates per meter of furnace width in waterwall boiler systems approximate 10 million kcal hr^{-1} m^{-1}. The primary furnace volumetric heat release rate approximates 90,000 kcal hr^{-1} m^{-3}

Energy markets (a beneficial and lucrative application for the recovered heat) are important to justify incorporating energy recovery into an incinerator design. Energy markets may be characterized in four ways.

- *The size of the market* – very large markets are desirable to assure absorption of 100 percent of the energy recovered. For this reason, sale of electricity into the (essentially bottomless) grid is very attractive;

- *The energy type* – steam markets are preferred over electricity (to eliminate the capital and operating cost for steam-to-electricity conversion, switchgear etc.);

- *The long-term market reliability* with which energy can be sold (risks of market stability over the lifetime of the financing); and

- *The short-term reliability of revenues* (the risk of reduced steam use arising from seasonality effects on space-heating load or process changes).

6. Ash Removal and Handling

Municipal solid waste includes inert materials that cannot be destroyed in the combustion process. Also, the incineration process is inherently imperfect so that some potentially combustible material is dried, heated and carbonized but the desired next step (gasification of the char) is not achieved. Further, some material simply “falls between the cracks” of grates (siftings) and leaves the hot combustion environment substantially unburned. These three components comprise bottom ash, the inevitable residue of municipal solid waste incineration operations. Municipal incinerator ash is usually characterized as:

> *Bottom ash*: the ash that falls from the grate combined with the siftings that fall through the grate; or
>
> *Fly ash*: the fine ash that becomes airborne in the primary chamber and either settles in the ducts and devices of the incinerator or, ultimately, becomes the inlet loading of particulate matter to the air pollution control system. The fly ash includes refuse constituents that volatilize in the high temperature zones of the furnace and, subsequently, condense on particulate and reagents (e.g. lime) added for acid gas absorption. Fly ash may include heavy metals and high molecular weight hydrocarbons with a significant health effect.

The presence of ash imposes several technical and economic stresses on the incineration operation and the incineration business:

- Since ash is a solid and cannot simply be drained from the incineration system, costly and high maintenance devices are needed to remove the solids from the combustor and to handle the ash stream.

- Ash (especially the smaller particles in the fly ash) is a concentrate of toxic elements such as lead, nickel and mercury as well as elements that are both carcinogenic and toxic such as cadmium, hexavalent chromium, and arsenic.

- Ash constitutes a waste stream of the incinerator and a place must be found to get rid of it. This generates an operating cost for both transport to its disposal site and for the disposal itself. Potentially, landfill disposal leaves the incinerator firm with a liability for groundwater contamination and other adverse short and long term consequences of residue disposal.

- Ash hazards (real or imagined) have emerged in many countries as a significant concern among the public and the regulatory agencies. These concerns can be addressed but they can be an impediment to project implementation.

- Ash (especially bottom ash) is variable in its properties including both large clinkers and fine dusts, it may include both massive and wire metals and ceramic and stony materials, and it exhibits a variety of colors, mechanical strengths and other physical and chemical properties. Other than by the extraction of ferrous metal (easy to accomplish with a simple magnetic separator), processing the residue to adjust its properties to meet the demands of the marketplace can be quite costly in comparison to the modest revenue stream that can be expected.

All of these factors can be important in making the environmental assessments, developing the operating strategy and carrying out the economic analysis concerned with municipal solid waste incineration.

a. Bottom Ash

After complete incineration of the refuse, the ash residue drops into an ash chamber or chute from the end of the grate or kiln. In some instances, a roller is located at the discharge point on the grate to allow the operator to hold back the residue to allow material to burn further or when there is a problem with the ash discharger or ash handling conveyors.

Siftings that have fallen through the grates (which may have been either partially or completely burned) and collected fly ash also may be conveyed to this ash chamber. The ash may be discharged directly into a container or onto suitable conveyors for disposal, or into water for quenching and cooling. The ash residue is then removed from the water with a hydraulic ram, drag conveyor, pusher conveyor, or other means.

To prevent in-leakage of air (disrupting the combustion air balance in the furnace) or out-leakage of furnace gases at the point where the gas is removed (impacting on air quality in the working environment), a positive air seal is necessary. Dry mechanical seals and seals made by covering the ash receptacle or container have been used to control air leakage. With wet removal of the ash, a wet or hydraulic (water) seal is used or a combination of a wet and mechanical seal is used. In order to keep this critical subsystem of the incinerator functioning, designs must incorporate features of ruggedness, flexibility and resilience. Weak, undersized ash handling systems will cause shutdowns.

1) Wet Systems

In most plants in the United States, Europe and Japan, the ash is quenched in a water trough at the discharge end of the grate. Most plants use a discharge plunger ram to push the quenched ash up an inclined ramp (to drain superficial water) discharging to an apron or vibrating conveyor. Older U.S. incinerator designs and small modular units quench grate residue in a trough filled with water (to provide an air seal) with a drag-chain conveyor running in the trough to pull out the quenched residue.

2) Dry Systems

If a dry system is to be used, means are required to assure that (1) ash is dumped frequently (avoiding excessive build-up) and (2) door opening actions are properly sequenced so that only one door to the combustion chamber is open at any one time.

b. Siftings

Siftings are the fine material that drops through openings in the grate into the air plenums. Screw conveyors or other appropriate materials handling systems are used to move the siftings to the bottom ash discharge point.

c. Fly Ash

Dry fly ash handling is usually provided using an enclosed screw conveyor. These conveyors are low in cost and efficient to handle the fine dusts collected in electrostatic precipitators and bag houses. In the simplest configuration, the fly ash is simply combined with the bottom ash. However, environmental regulatory agencies may require separate disposal of bottom ash and fly ash.

d. Materials Recovery from Ash

In a few plants, the bottom ash is processed for ferrous metal recovery. In a few instances, additional processing of the residue yields materials useful as a fill or for road construction.

1) Ferrous Metal Recovery

In the United States, Japan and Europe the quantity of ferrous metal in incinerator residue ranges from 6 to 9 percent by weight. The technology of ferrous metal recovery is simple, the capital and operating cost is low and the installation has little impact on plant layout or staffing requirements. Ferrous recovery is generally effected by use of a belt electromagnet. Most often, the magnetic belt is located at a transfer point for the residue conveyor and the recovered ferrous is cast into a chute to a second receiving container.

2) Roadbeds and Earthworks

Following processing for ferrous metal removal, the medium ash solids, such as clinker particles, portions of fused glass, or particles of shattered glass that pass the magnet can sometimes be screened for use as fill material or for use in surfacing and construction of alleys and secondary streets [1].

7. Pollution Control

An incinerator is probably of greatest concern to a municipality because of the fear of the air pollution impact on the contiguous environment. The “emission factors” characterizing the relationship between waste properties, design and operating parameters and the uncontrolled emission rates and the effectiveness of options in abatement technology are major technical areas and are dealt with in comprehensive incineration texts [1] and in other courses.

Water pollution from the process drains and blow down and from residue disposal is a secondary issue in comparison to air emissions but still merits careful consideration and control. Also, an incinerator can create undesirable noise and cause the surrounding area to be unattractive because of vehicle traffic, collection truck litter and other forms of trash which quickly disfigure an incinerator site where good housekeeping is not regarded as a fundamental plant responsibility.

a. Air Pollution

The most noticeable forms of air pollution are fly ash, smoke, odors (from the stack as well as other areas), noxious gases, and dust. Honesty would require acknowledgement that all of these will emanate from an incinerator at times. However, the net impact (health and aesthetic) of these emissions, as mitigated by the normal buffering area around the plants and high levels of control, is negligible.

1) Composition of the Flue Gases

If combustion of the volatile fraction of the refuse is complete, the composition of the flue gas will be principally nitrogen, oxygen, water vapor and carbon dioxide. There will also be small amounts of sulfur oxides, nitrogen oxides and mineral acids (principally hydrochloric acid, which will result from the combustion of halogenated plastics, particularly polyvinyl chloride). Normally, the concentration of sulfur oxides, nitrogen oxides, and mineral acids will be high enough so that they will trigger the regulatory requirement for air pollution control. If combustion of the volatile is not complete, the flue gases will contain carbon monoxide and other unburned or partly burned organic materials (“volatile organic compounds or VOCs). These emissions are more subtle but can include the polychlorinated dibenzo p-dioxin and dibenzo furan compounds, POMs and the like. The first easily visible indication of the presence of these materials in high concentrations will be the appearance of black smoke from the incinerator stack, which may be followed by the detection of objectionable odors.

The presence of unburned or partially burned materials is unnecessary and is caused by the poor operation of the incinerator. Their emissions can and are controlled by the proper operation of the incinerator rather than the installation of control devices. Complete combustion can be assured by operating the incinerator (after the last point of air injection) at high temperatures (from 750 to 1000°C); by providing sufficient air for combustion; by providing sufficient residence time for the combustion process to occur; and by inducing (by both gas passage configuration and well designed overfire air jets) sufficient turbulence in the combustion space to mix the combustible gases and aerosols with the necessary air. Modern units achieve these goals using sophisticated monitoring and control of the combustion environment. Also, catalysts can be incorporated into fabric filters to enhance dioxin destruction.

Such residence time and some mixing are usually provided for by ducting the flue gases to a secondary combustion chamber or zone. Although it is not essential that a discrete second chamber be provided, it is necessary to provide sufficient volume in the furnace, preceded by vigorous induced mixing at elevated temperature to assure that the combustion process is completed. Few single-chamber incinerators meet this requirement.

2) Control of Particulate Matter and Acid Gases

Particulate matter (characterized by flue gas weight loading), generally referred to as fly ash, is generated in and elutriated by the combustion process and must be removed from the effluent gases. The amount of particulate matter which is generated is somewhat dependent upon the design and operation of the incinerator. If the combustion process is not complete, a sooty fly ash will result.

Studies indicate that there is a correlation between the amount of fly ash entrained in the effluent gases and the distribution and amount of overfire and underfire air and the type of grate employed. No matter how carefully the incinerator is operated, however, particulate matter will be entrained in the effluent gases. In a properly designed and operated incinerator, equipped with appropriate air pollution control equipment, all of the stringent standards established by states and the federal government can be met.

Although the flue gases from incinerators contain a number of pollutants, air pollution control equipment installed on these units is primarily directed at the problem of particulate removal. For this purpose, a number of devices are in use, ranging in particulate removal efficiency up to above 99%. In light of present and forecast particulate emission standards throughout the world, control efficiencies in excess of 98% are generally required and routinely achieved.

Electrostatic precipitators (ESP) and fabric filters are commonly used for particulate removal from incinerator flue gases. Both systems can be used in conjunction with a spray dryer absorber where fine droplets of a slurry of lime are injected at temperatures where total evaporation results yielding highly reactive alkaline particles that absorb both SO_2 and HCl. The fabric filter is preferred since it has a higher fine-particle control efficiency (important in metal control) and it offers the advantage that the captured filter cake gives a second contact opportunity for acid gas control in comparison with an ESP when used with a spray dryer absorber. Also, as noted below, it has been observed that the normal working temperatures of ESPs are ideal for the formation of dioxin compounds, an undesirable byproduct characteristic.

A WTE plant with three spray dryer absorber systems installed is shown in Figure 7. On the right is the lime silo. Just to the left of the silo are the cylindrical absorber evaporation chambers. To their right are the three fabric filters.

3) Control of Trace Pollutants

"Dioxin," the popular name given to the mixture of polychlorinated dibenzyl-p-dioxins (PCDD) and furans (PCDF) compounds formed in municipal incinerators and mercury and its compounds have had a profound impact on the design, operations and public acceptability of WTE facilities. Bench-scale experiments have provided convincing evidence that PCDD/PCDF compounds are created downstream of the furnace: a catalytically assisted reaction on the surface of carbonaceous fly ash. Maximum tetra- to octa-PCDD and PCDF formation occurs near 300°C. PCDF also shows a lower peak generation rate near 450°C. As the temperature falls below 250°C, the reaction rate falls quickly to near zero. The precursor materials involved are simple: carbon char and inorganic chlorides. Most researchers do not show a correlation of CDD/CDF generation with the HCl concentration in the flue gases and there has been no conclusive scientific evidence that specific solid waste components (such as PVC) are responsible for any significant fraction of the total CDD/CDF. Control of this pollutant has been effective: achieving good combustion of char in the hot zones of the furnace ("Good Engineering Practice" combustion) and the use of dry scrubber technology for acid gas control that quickly cools the flue gases below the dioxin formation zones. Also, dioxin reduction is achieved when activated carbon is injected into the flue gas stream (ostensibly for mercury control), by using fabric filters incorporating catalysts that degrade dioxins and with catalytic dioxin destruction means downstream of the fabric filter. These technology options are discussed in other resources [1].

A second pollutant of concern relates to the concentration and emission chemistry of mercury and its compounds. Almost all of the mercury in the feed waste appears in the furnace gases (rather than the bottom ash) because of the high volatility of elemental mercury (boiling point 357°C) and the fact that all of its compounds decompose at relatively low temperatures. The chemistry of mercury in the flue gases has an effect on the accuracy of mercury emission data: elemental mercury (Hg or Hg_2), mercuric or mercurous chloride ($HgCl_2$ or HgCl) mercuric or mercurous sulfide (HgS or Hg_2S) etc. The chemistry-related effects result from the impact of physical form (gas or solid) and/or reactions in the sampling train on reported mercury quantities.

The strong absorption of mercury and its compounds by activated carbon has led to the addition of this reagent to incinerator flue gases (at the back end where temperatures are reduced). The carbon is added either in dry form or in combination with lime in the dry scrubber lime slurry. As a second benefit, activated carbon also has an affinity for high molecular weight hydrocarbons including the dioxin compounds, polynuclear hydrocarbons (PNHs) and the like.

In general, the uncontrolled mercury emission in MWCs has decreased as battery manufacturers (a major source of mercury in MSW) have shifted to new electrochemical concepts. Also, many of the medical uses of mercury including both mercury-containing medicinals (such as calomel creams) and equipment (e.g., blood pressure devices and thermometers) have declined.

Fig. 7 Spray Dryer Absorber System on WTE Plane

8. Fans and Stacks

These topics are covered in the Fundamentals of Combustion, Part 2 course.

9. Overall System Integration

As noted in the introduction to this course, the integration of all of these system elements into a total WTE facility is unique to each of several system vendors. What is important is their continuing investments in research, drawing on their extensive experience base and existing plants (acting as available piloting facilities) to enhance the performance and controllability of their particular embodiment of the mass burn concept. An example of such integration is shown in Figure 8: the original Harrisburg, PA Martin grate design (steeply sloped reciprocating grates pushing “up-hill”), with electrostatic precipitator air pollution control.

D. Refuse Derived Fuel Systems

Refuse Derived Fuel (RDF) systems are incinerator furnaces where the waste is processed prior to combustion with the objective of significantly reducing its level of heterogeneity. The strategic concept of processing heterogeneous solid waste prior to combustion has several potential virtues:

- In the course of processing, portions of the waste can be recovered and recycled. Thus, materials recovery can be an inherent partner in on-going or new resource recovery programs.

- The processing line can be designed to produce a more homogeneous fuel. This should stabilize the combustion process, facilitate more precise combustion control, improve burnout, produce a more stable steaming rate etc. Since separation processes can remove stones, glass and wet material, the mean moisture content of the waste can be reduced and the combustible content enriched thus increasing the heat recovery potential. Further, one would expect that with better combustion control, excess air levels can be lower thus reducing the capital cost and many operating expenses for incinerator furnaces, boilers, fans and air pollution control devices.

- Improved combustion should reduce air pollution emissions related to unburned or incompletely burned combustibles. Further, because of the materials recovery steps, emissions related to specific waste components (e.g., PVC) can be reduced.

- Because the processed material are more regular in physical characteristics (e.g., particle size), materials handling should be easier to automate and should work better.

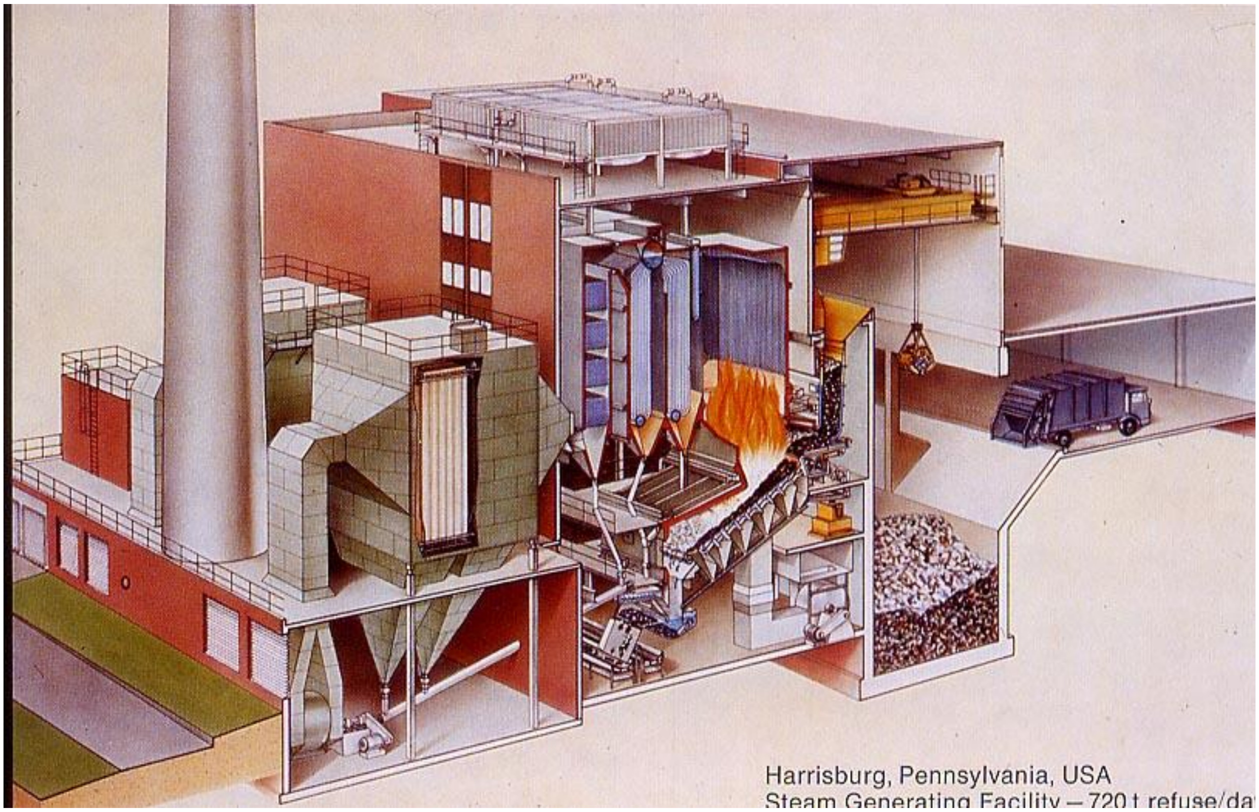

Fig. 8 Harrisburgh Pennsylvania Martin System

It was recognized that these benefits would come with some cost: the capital and operating cost increases associated with the processing systems, an increase in the fraction of the incoming waste (typically 20-30%) that is bypassed directly to landfill, some environmental problems (esp. noise and dust from shredder and conveyor operations), and risk of injury or equipment outage due to explosions. All of these anticipated "costs" and some that were not anticipated have, indeed, been experienced; and often at an unanticipated degree of severity and consequence.

In the development and implementation of technology for mass burn facilities, the vendor firms participating in the market generally offer complete “chute-to-stack" systems based on conservative, repeat application of well-proven technological features. Most aspects of the mass burn technology were extensions of combustor concepts developed and proven in burning coal, lignite and waste fuels such as bagasse. In contrast, many RDF plants incorporate innovative process flowsheets and experiment with untested and unproven items of equipment in the critical RDF processing and handling areas. The extensive body of design data that supported the early mass burn incinerator designs was lacking for RDF systems. Further, the lack of overall system vendors for RDF-based systems reduces the feedback of field experience into process development.

The often-demonstrated characteristic of refuse to profoundly stress, clog, abrade, corrode and otherwise challenge process and handling equipment made extrapolations from prior experience with other materials uncertain and, quite often, disappointing. Further, the prime RDF processing devices were connected together with materials handling systems where critical design parameters were not well understood and where refuse behavior often was found to be "quite different" from that of reference materials used as the basis for design.

The consequences of these facts and influences were repeated in many if not all plants: long and politically painful start-up programs requiring considerable re-work of conveyors and processing equipment. This was accompanied by increases in facility capitalization, higher than anticipated operations and maintenance costs and, often, derating of the combustor due to limitations in processing and/or feeding systems. Also, from time to time, many plants experienced explosions, some with lethal consequences, from ignition of combustible vapors released in hammermilling of volatile hydrocarbon (e.g., gasoline) containers.

Despite these challenges and failures, a maturing technology ultimately emerged. By the early 1990's, "package" RDF processing facilities with performance guarantees could be procured to generate specification RDF. A vendor community offering total RDF-based systems was developing. RDF-only and co-combustion of RDF with other wastes and/or coal was being practiced in several incinerator boiler and utility power plants throughout the United States. The basic technology had become generally "available." The primary concerns limiting implementation of RDF-based projects had shifted from one of high perceived technical risk and problematic operability to the more conventional project development decision criterion: the ordinary issues of cost, permitting, siting, and the like. It may be significant, however, that now new RDF-based systems have been installed in the U.S. in recent years and several jurisdictions with RDF systems that have ended their useful life are upgrading or exchanging to mass burn alternatives.

1. RDF Processing

The underlying objectives of incineration using RDF (materials recovery and production of a homogeneous fuel) are achieved in the processing line. It is here that materials for recycling are recovered (on "picking belts" by human workers or by automated processes that exploit the physical or chemical characteristics of target refuse components). Before or after the removal of materials, size reduction and size separation takes place. In all cases, the RDF facility is heavily involved in materials handling equipment to include a spectrum of loaders, conveyors, hoppers and feeders. Processing alternatives, performance and utility requirements are described elsewhere [1]. The perverse nature of refuse with conventional materials handling processes has been the major problem with RDF plants.

2. RDF Combustion Systems

The combustion concepts used in burning RDF fall into two categories: RDF-only combustors and combustors where RDF is burned as a second fuel along with coal, wood waste or other materials. Since almost all processing concepts include size reduction and the removal of massive metal material, stones, much of the glass and the very wet wastes, the remaining fuel is well-suited for partial or complete combustion in which the particles of RDF are suspended in gas flows. RDF is poorly suited for mass burn grate burning as it tends to blind the grates and inhibit air flow. Consequently, the types of combustion system used for RDF have focused on the spreader stoker (semi-suspension burning) using a chain grate (Fig. 5) and several embodiments of full suspension firing.

a. Spreader Stoker Firing

The spreader stoker furnace uses a single, flat traveling grate. The grate moves at a slow, constant rate much as a conveyor belt. Air is supplied through the grate from one or more undergrate plenums. Waste supplied to the furnace is typically shredded such that about 95 percent passes a 10.2 cm top-size. Wastes are charged to the furnace using several mechanical or air-swept feeders mounted on the "front face" of the furnace wall. The feeders cast the feed over the fire to land on the grate near the rear wall. The grate moves the waste back toward the front face and discharges ash just below the feeders. All but the very wettest RDF feedstock is dried and ignited in its flight across the furnace through the flow of hot combustion gases rising from the grate. After landing on the grate, the waste continues to burn. For design purposes, it is often assumed that 40 to 60 percent of the heat release takes place in suspension and the remainder on the grate.

Although the RDF preparation step can produce a fuel with considerably greater homogeneity than raw refuse, the benefits of homogeneity require a steady feed rate. Achieving a uniform feed rate has not proven easy. Hang-ups and blockage occur in almost all systems. This results in irregular feed rates, heat release and steaming rates.

b. Suspension Burning

The burning of RDF is suspension has been effected in two ways:

- In solid fuel boilers using feeding methods that are similar to those used to fire pulverized coal in suspension and in vortex furnaces; and
- In fluid bed combustors.

In each case, secondary fuels (coal or other waste streams such as wood scraps, sawdust agricultural wastes or industrial liquid waste) are often burned at relative heat release rates ranging from zero to many times that of the RDF.

a. RDF and RDF-Coal Burning in Suspension-Fired Boilers. Co-burning of refuse and coal is significantly different from burning either fuel alone. With co-burning, the combustion environment must be tailored to the limitations imposed by the poorest fuel. The furnace temperatures will approach that of the dominant (heat release basis) fuel.

The top-size of the RDF used in suspension burning has varied from as small as 0.95 cm to as much as 6.35 cm. The cost of shredding increases rapidly as the mean particle size decreases. However, larger particles have longer burning time. One should avoid carry-over of burning RDF fragments because (1) the material can generate clinkers during burnout in the ash hoppers under the boiler passes or, (2), if applicable, burning "sparklers" cause pinholes in fabric filters. Therefore, the goal has been to find the largest top size that gives acceptable combustion and minimum carry-over of burning material from the primary furnace. A maximum particle size between 2.5 and 3.8 cm appears optimal. A cross-section of the coal-RDF boiler used in Ames, IA is shown in Fig. 9.

From a regulatory standpoint, co-burning RDF and coal offers a significant advantage in comparison to RDF alone. If the heat release rate due to the refuse is less than 15% of the total heat release, the special U.S. EPA air pollution emission requirements applicable to “incinerators” does not apply: only the conventional coal emission requirements. This is an advantage in both permitting and in gaining public acceptance of the system.

b. Fluid Bed Burning. Fluid bed incinerators for RDF were described earlier. Fluidized bed RDF combustion can involve new plant, stand-alone combustors (followed by boilers) or modification of existing coal furnaces (suspension fired or stoker fired) to add the distribution plate, high pressure air supply, sand management and other features of a bubbling fluid bed. RDF, coal, wood or almost any other feedstock that is compatible with a reasonable overall energy balance can be fed to the bed. Critical requirements are features that can adequately handle the segregation and discharge of the noncombustible, "tramp material" fed to the system an in-bed boiler tubes to effect heat removal from the bed. Heat removal allows control of bed temperatures and avoids ash fusion and bed defluidization. Facilities meeting these requirements were installed in La Crosse, WI and Tacoma, WA.

E. Modular Incinerators

In the 1960s, several manufacturers, recognizing the increasing emphasis on smoke abatement, began producing incinerators which limited (or starved) the combustion air supplied to the primary chamber to about 80 percent of theoretical and the overall combustion air to about 120 percent excess. This holds flue gas temperatures high and minimizes the need and/or fuel consumption for afterburner devices.

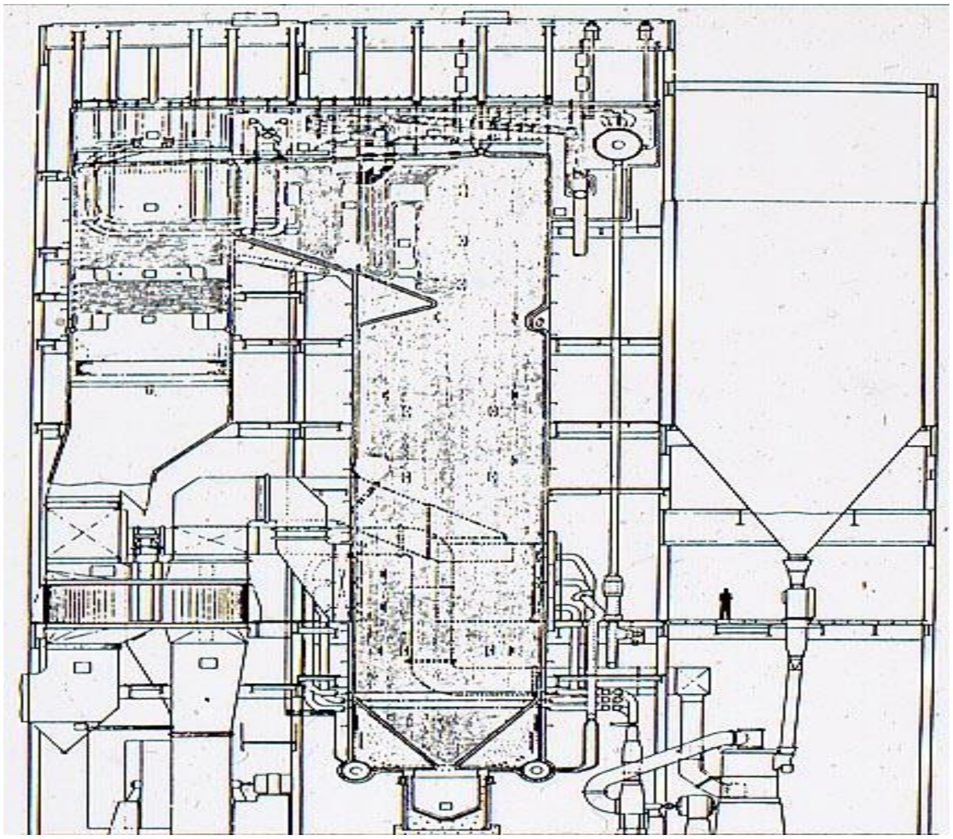

Figure 9. Suspension-fired Boiler for RDF and Coal

The starved air units consist of a cylindrical or elliptical cross-section primary chamber incorporating underfire air supply (Fig. 10). Overfire air is also supplied (to a limited extent) in the primary chamber. The low total air supply minimizes the carryover of particulate. The lower chamber temperature is maintained at 700 - 750 °C) to minimize the fusion of glass (clinker formation) but the combination of low temperature and limited air leads to a sacrifice in the burnout quality. All combustion air is provided by forced draft fans. In many such incinerators, the proportion of underfire to overfire air is regulated from a thermocouple in the exhaust flue: higher primary temperatures increase overfire air and decrease underfire air.

Gases leaving the primary chamber contain a substantial concentration of carbon monoxide, hydrogen, light hydrocarbons etc. The gases are passed to a secondary chamber (Figure 10-A) or to an in-stack afterburner where the remaining combustion air is added. A pilot flame assures ignition. Most units incorporate a gas or oil burner in the secondary or afterburner chamber for use during startup, shutdown and when refuse heat content is insufficient to achieve regulatory minimum operating temperatures. The burner is energized whenever the gas temperature falls below the set-point temperature. In some configurations, the afterburner is mounted in the refractory-lined stack.

Starved air incinerators are available in capacities from 100 to 3,000 kg/hr. In the larger, units (Fig. 11), one or more air-cooled rams can be incorporated into the design of the primary chamber to push and gently mix the waste in the unit and expel ash. The larger units incorporate hydraulic ram feeders (with air-lock covers and guillotine dampers at the furnace entrance), quench tanks and drag conveyors to

provide for continuous ash removal. This type of feeding method is discussed in the Solid Feed section in the Fundamentals of Combustion – Part 2 course.

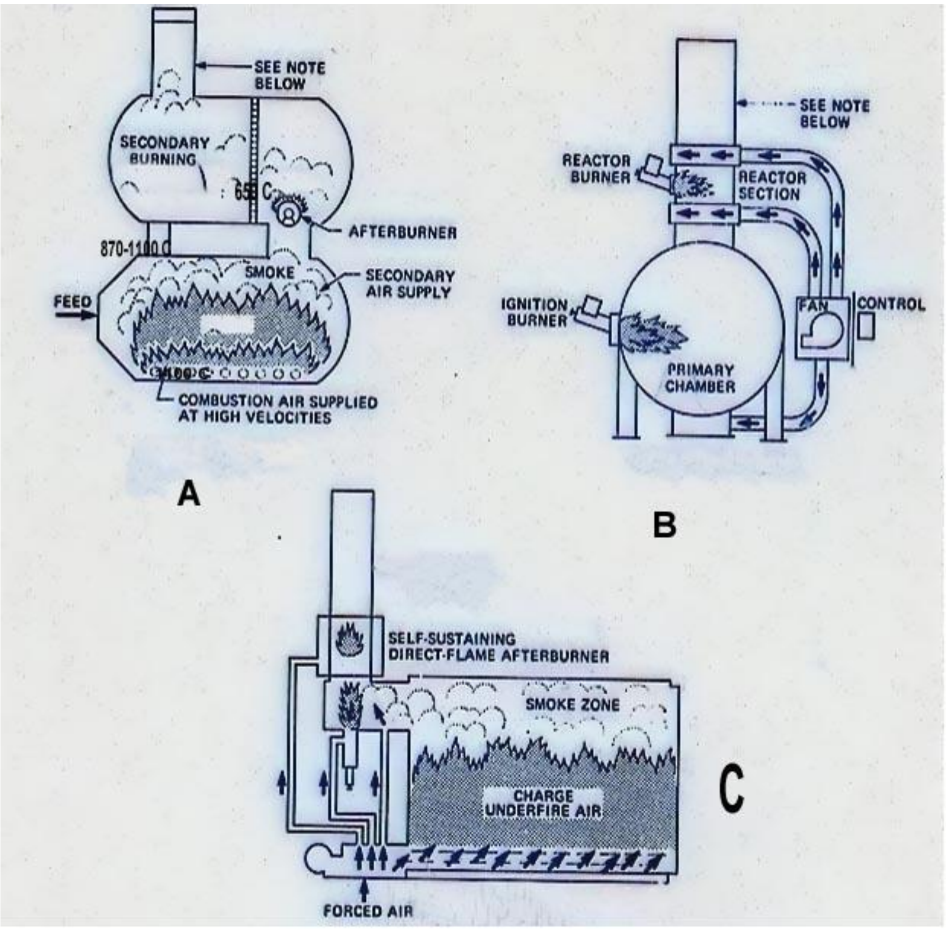

Figure 10. Basic Features of Modular (Starved air) Mass Burn Units

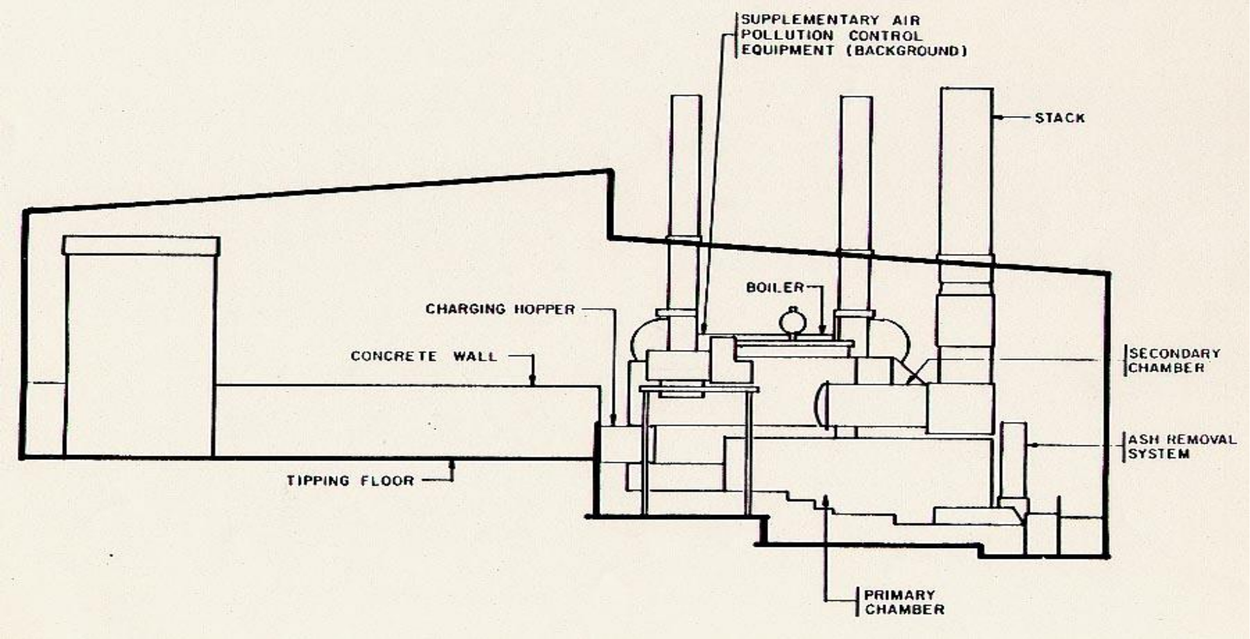

Fig. 11 Large, Modular Combustion Units (MCU) Facility

F. Operations

A comprehensive treatment of the operating problems and challenges of municipal waste incineration would introduce many new topics. Further, the "rightness" or "wrongness" of many of the recommendations would be subject to controversy since the human element, leadership styles, cultural effects and the like often produce many good and workable answers to the same question. However, there is merit is identifying the major operating problems observed in existing plants as indications to the design engineer that attention is necessary.

Experience based on a study of the equipment of approximately 30 manufacturers in 52 mass burn and modular incineration plants with heat recovery [6] indicate that refractory problems are the most common, ranging from the need for minor patching to complete replacement. Minimization of the problem included both attention to avoid charging bulky, metal wastes and replacement of (softer) castable refractory with more abrasion-resistant, fired brick. Ash conveyors and problems with controls were also common. In modular combustion units, underfire air ports were subject to plugging and problems with the charging ram were common. Enlarging of the orifices and periodic steam purging have been tried to help the problem, but regular maintenance and cleaning is still necessary. Systems with fire tube boilers also had plugging and corrosion problems.

Many plants complain about the limitations caused by a small tipping floor that causes congestion during deliveries and does not give room for floor-dumping to inspect incoming waste for auto batteries, hazardous wastes etc. as may be required by local authorities. Also, complaints called for more attention by the designer to the potential traffic flow pattern on the tipping floor.

Warping of dampers and charging doors was also common; especially in starved air systems and when units are run at higher than design temperatures. Similar problems with charging rams were noted although deficiencies in the hydraulic systems were the prime source of the difficulties.

G. Summary

The sections above provide an introduction to full-combustion alternatives in the thermal processing of domestic solid waste. There is much more to learn but the insights above provide the basics needed to understand conventional mass burn and RDF systems; presently responsible for the processing of almost 15% of the waste now generated in the United States. A second course, Thermal Processing of Domestic Solid Wastes – Conversion Technologies (gasification, plasma systems etc.) builds on this foundation and indicates the direction of innovation in this important public services area.

One should realize, however, that the technologies described in the full-combustion course are the “gold standard.” Particularly for the mass burn options, these systems are offered through multiple source competition between experienced firms with impressive and extensive track records in meeting budgets and schedules and which meet or better all air, water and residue-related federal and state regulations. These features should not be taken likely given the aggressive and unforgiving behavior of domestic waste.

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