DESIGN AND OPERATING EXPERIENCE WITH HIGH TEMPERATURE AND HIGH PRESSURE REFUSE-FIRED POWER BOILERS

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ABSTRACT

The typical U.S. refuse-to-energy facility utilizes a 600 psig, 750°F steam cycle. The ability to operate at higher steam pressure and temperature cycles, without incurring excessive corrosion, results in more kilowatts per ton of refuse and, hence, more economically attractive projects. This paper represents the evolution of a 900 psig, 830°F refuse boiler from lower temperature and pressure cycles, and the operating experience gained through the processing of over 4,500,000 tons of refuse.

INTRODUCTION

The incineration of municipal refuse is not a new idea, in fact, it has been practiced in Europe and the United States since the early 1900s. However, the combustion of municipal refuse in large capacity, high steam pressure and high steam temperature power boilers is relatively new. The increased pressure, and temperature of these refuse boilers, coupled with the higher Btu, higher chloride content of domestic refuse, presented new challenges to refuse boiler designers and operators.

In March 1984, three 750 ton per day (TPD) (680 tonnes/day) Babcock & Wilcox (B&W) refuse boilers, operating at 900 psig (6205 kPa) and 830°F (443°C), commenced operations at Wheelabrator Environmental Systems' (WES) refuse-to-energy facility in Peekskill, New York (Westchester County). In September, 1984, three identical units were started up at a similar refuse-to-energy facility in Baltimore, Maryland. As of January 1988, these six units have processed over 4,500,000 tons of refuse. The Westchester boilers were designed in the fall of 1981. At that time there was limited operating experience with large capacity, high steam temperature boilers firing U.S. refuse, on which to base the Westchester boiler design. The design features of these boilers and their operating experience will be discussed in this paper.

BACKGROUND

As of 1966, there were nearly 300 refuse incineration facilities in the United States with a combined refuse incineration design capacity of approximately 30,000,000 tons of refuse per year [1]. Incineration of municipal refuse in the U.S. is not new, but today it is different.

Most experience with the mass burn incineration of municipal refuse has been centered in Europe. In response to the needs of the European refuse market, the European mass burning technology has evolved from incinerations only, with no heat recovery, to incineration with low pressure hot water boilers, to incinerators with low pressure steam boilers for use in district heating plants, to today's units which typically are designed for 600 psig (4137 kPa), 752°F (400°C) high pressure steam. As late as 1976, a survey of 14 European countries showed that of those having refuse incinerator plants with heat recovery, 34% of the plants were still used only for the production of hot water, while only 16% were designed specifically for the generation of electric power from high pressure steam [2].

In the U.S., the refuse-to-energy business began to grow in the early 1980's in response to tax incentives for private ownership of refuse-to-energy facilities and the Public Utilities Regulatory Policies Act (PURPA) of 1978. Essentially PURPA required U.S. utility companies to purchase power from refuse-to-energy facilities, and other small power generation facilities, at the utilities' avoided cost of power generation. Because of the U.S. refuse facilities' dependence on the revenue from electric power sales, refuse boiler designers were driven to develop high combustion efficiency, high refuse throughput, and high steam pressure and temperature boilers. While the main goal was still to dispose of the refuse in an environmentally safe manner, it also had to be done in a fuel efficient manner. The most common high pressure steam cycle for refuse plants in both the U.S. and Europe had previously been typically a 600 psig (4137 kPa), 752°F (400°C) steam cycle. In contrast, the 900 psig (6205 kPa), 830°F (443°C) steam cycle can produce over 16% more kWh/ton of refuse burned than the more typical 600 psig (4137 kPa), 752°F (400°C) steam cycle [3]. To maximize electric power production, the 900 psig (6205 kPa), 830°F (443°C) steam cycle was chosen for the Westchester boiler design.

Most of the early U.S. refuse-to-energy plants were located in high density population areas. Also, with the economic desire to generate as much electric power as possible, the majority of the early U.S. refuse facilities were large refuse capacity plants. Typically, these refuse facilities ranged in size from 800 TPD (726 tpd) to 3000 TPD (2722 tpd) resulting in fairly typical mass burning refuse boiler capacities from 400 TPD (363 tpd) to 750 TPD (680 tpd). Non-U.S. refuse boilers tend to be lower capacity boilers. As can be seen in Table 1, of the 1654 non-U.S. refuse boilers listed, 99.7% are less than 750 TPD (680 tpd) capacity and 93.8% have a refuse boiler capacity of less than 400 TPD (363 tpd).

Many of the early U.S. refuse-to-energy facilities encountered operating problems. Builders discovered that European refuse was not at all like domestic refuse. For example, U.S. waste contains a higher volume of plastics, which produce high temperature and corrosive gases. In general, furnace temperatures, when firing U.S. refuse, were found to be higher than predicted, based on European refuse experience.

TABLE 1 NON-U.S. REFUSE OPERATING EXPERIENCE

CAPACITY	NUMBER OF UNITS	PERCENT OF TOTAL
Less than 200 TPD (1B1 tPD)	1102	66.6%
200 TPD (181 tPD) to 249 TPD (226 tPD)	161	9.7%
250 TPD (227 tPD) to 299 TPD (271 tPD)	81	4.9%
300 TPD (292 tPD) to 399 TPD (362 tPD)	209	12.6%
400 TPD (454 tPD) to 499 TPD (453 tPD)	44	2.7%
500 TPD (454 tPD) to 599 TPD (543 tPD)	36	2.2%
600 TPD (544 tPD) to 749 TPD (679 tPD)	16	1.0%
750 TPD (680 tPD) and Greater	5	0.3%
	1654	100.0%

SOURCE: 1985 and 1986 Experience Lists published by DeBartolomeis/Deutsche Babcock Analagen/Martin/Seghers/Steinmueller/Takuma/Volund/Von Roll/Widmer and Ernst.

At the Saugus, Massachusetts Refuse Facility, which began operation in 1975, the superheater experienced random failures after just 2000 hr of operation [4]. The WES operated Pinellas County Refuse Facility, which began operation in 1983, suffered similar premature superheater tube failures. Furthermore, the first two boilers at the Nashville Refuse Facility, which went into operation in 1974, encountered many problems during their early operating history, including superheater and boiler tube failures [4]. The newest refuse boiler at Nashville, placed in operation in 1986, has benefited from the years of operating experience with domestic refuse at the Nashville facility and elsewhere in the U.S., and has now been in operation for nearly two years with no significant operating problems [5]. Actual operating experience with the specific fuel to be fired in the boiler provides the most meaningful design experience, which can then be translated into a conservative gas side design.

In summary, at the time the Westchester boilers were designed, there was little available operating experience at 750 TPD (680 tpd) refuse capacity and 830°F (443°C) steam temperature, in addition to any design considerations necessitated by the uniqueness of U.S. refuse.

THE WESTCHESTER REFUSE BOILER DESIGN

It is important to note that refuse boilers are thermal input machines, i.e., the design consideration is the

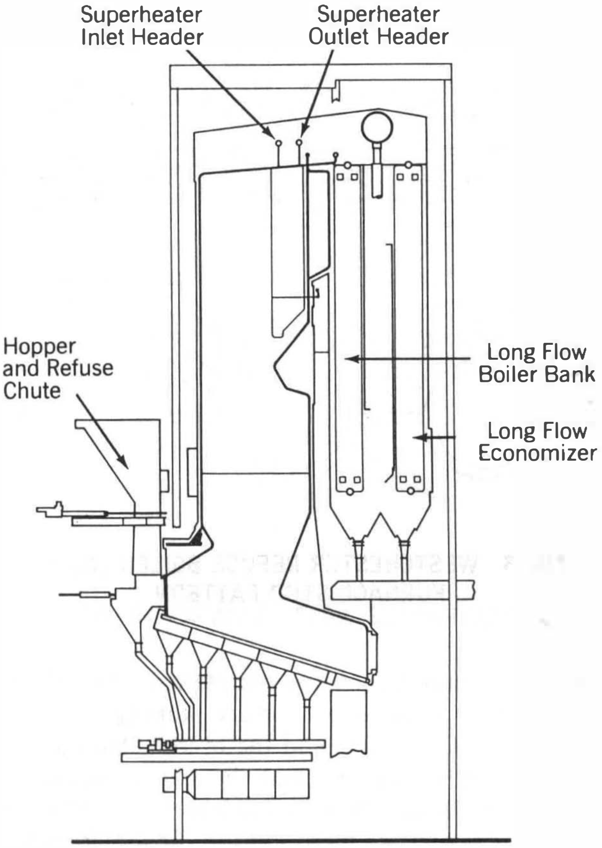


FIG. 1 WESTCHESTER 750 TPD REFUSE BOILER SIDE VIEW

quantity of heat released from the combustion of refuse. Steam production is secondary and results from the amount of fuel fired. This is contrary to typical power boiler design where the design consideration is a specified steam output and the unit's efficiency determines the quantity of fuel required. For refuse-fired boilers, this is further complicated because the heating value of refuse varies widely. An input of 750 TPD (680 tpd) of 3800 Btu/lb (8835 J/g) refuse is much different than an input of 750 TPD (680 tpd) of 5200 Btu/lb (12,090 J/g) refuse. A refuse boiler designed for 750 TPD (680 tpd) at 5200 Btu/lb (12,090 J/g) could fire at 750 TPD (680 tpd) with 5200 Btu/lb (12,090 J/g) refuse or at a higher capacity with refuse having a higher heating value (HHV) of less than 5200 Btu/lb (12,090 J/g). For future reference, this paper assumes that a 750 TPD (680 tpd) refuse input is 750 TPD (680 tpd) at 5200 Btu/lb (12,090 J/g).

Boiler design must take into account the stoker configuration, furnace heat transfer, furnace geometry and the slagging and fouling characteristics of the fuel to be burned (which set flue gas temperature limits). The way these considerations were incorporated into the Westchester boiler design (Fig. 1 and Table 2) is discussed in the following sections.

TABLE 2 WESTCHESTER BOILER DESIGN PARAMETERS

PARAMETER	CONDITIONS	
Rated Capacity	750 TPD	(680 tPD)
Design Fuel HHV	5,200 Btu/lb	(12,090 J/g)
Design Steam Flow	192,000 lb/hr	(87 t/hr)
Steam Pressure	900 psig	(6205 kPa)
Steam Temperature	830°F	(443°C)
Feedwater Temperature	300°F	(149°C)
Gas Temperature Entering Superheater	1450°F	(788°C)
Furnace Volume	39,335 Cu.ft.	(1,114 Cu.M)
Furnace Volumetric Heat Release Rate	8,300 Btu/ft^3-hr	(223 kJ/m^3-hr)

FURNACE DESIGN CONSIDERATIONS

Furnace designs are set by the functional parameters of furnace exit gas temperature (FEGT), the physical requirements of the combustion equipment and combustion residence time. Once a furnace design has been selected, system designers will determine the volumetric heat release rate (VHRR). The VHRR criteria indicate that there is sufficient furnace volume for complete burnout and provide the design engineer with a useful check that the furnace selected is of sufficient size.

The necessity of maintaining high combustion temperatures for long residence times was recognized. It was also recognized that a furnace plan area approaching a square would produce the maximum furnace volume with the minimum of heat transfer surface in the water-cooled enclosure. Because this design would result in high furnace temperatures for maximum residence time, the furnace geometry approaching a square was selected. Flow modeling confirmed that the concept of the square furnace, in combination with the unique lower furnace arches and the total combustion system, would result in the best design for achieving the goal of environmentally acceptable emission levels.

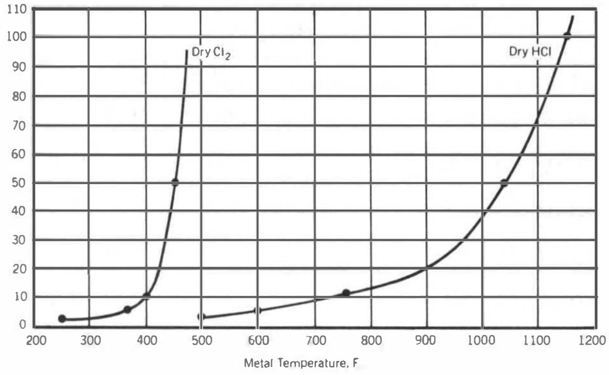


FIG. 2 CORROSION OF CARBON STEEL IN CHLORINE AND HYDROGEN CHLORIDE

Large capacity refuse boiler designs are set by maximum FEGT limits. The smaller capacity refuse boiler designs are set by furnace volume considerations and tend to have lower FEGTs, generally ranging from 1400°F (760°C) to 1200°F (649°C) or lower. As noted previously, 93.8% of the 1654 non-U.S. refuse boilers have capacities less than 400 TPD (363 tpd). It is, therefore, appropriate that the FEGT of these units be in this 1200°F (649°C) to 1400°F (760°C) range. The 750 TPD (680 tpd) mass-fired refuse boiler for Westchester has a design FEGT of 1450°F (788°C) and a design VHRR of 8300 Btu/ft^3-hr (223 kJ/m^3-h).

Various European refuse boiler designers utilize a single furnace pass design or a two-furnace pass design, with the second pass being an idle pass, or a three furnace pass design (with two idle passes). B&W utilizes the large volume, single furnace pass design with no idle passes. Of the European designers, both Von Roll and Deutsche Babcock Anlagen frequently utilize the single furnace pass design.

The combustion of refuse results in gases that have a high corrosion potential and all refuse boilers will be subject to some amount of corrosion. The rate of corrosion is directly related to tube metal temperature and tube metallurgy (Fig. 2). In addition, the rate of corrosion can be accelerated in a reducing atmosphere (a deficiency of O_2 below that needed for combustion) such as that often found in the lower furnace of mass-fired refuse boilers. Operating experience on mass-fired refuse boilers has dictated that the lower furnace tube metal be protected from the corrosive flue gas. Designs utilizing pin studs and silicon carbide refractory material coatings have effectively eliminated corrosion concerns in the lower furnace [6]. Today virtually all mass burn boiler designs incorporate some type of pin stud/silicon carbide lower furnace protection.

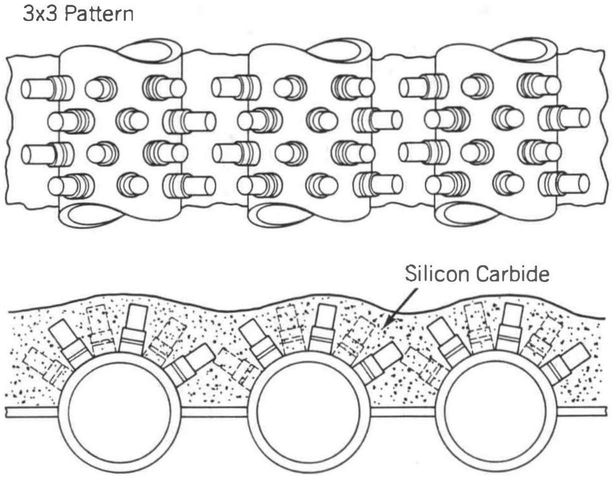


FIG. 3 WESTCHESTER REFUSE BOILER LOWER FURNACE STUD PATTERN

The size of the studs and the overall stud pattern are designed not just to hold the silicon carbide in place. Consideration must be given to maximizing the heat transfer through these studs to the furnace tubes to provide as much cooling and as low a refractory surface temperature as possible. Maintaining a low refractory surface temperature has a dramatic effect on refractory life, furnace wall fouling, and maintenance costs.

The pin stud design for the Westchester boiler (Fig. 3) utilizes 1 in. long, ½ in. diameter studs with a 3 × 3 pattern resulting in a pin stud density of 192 per square foot. The design chosen has been proven and utilized for many years in the lower furnace of black liquor-fired process recovery boilers.

SUPERHEATER DESIGN

Proper superheater design must include consideration of the flue gas temperature outside the tube, the temperature of the steam inside the tube, the spacing of the tubes based on fouling criteria, and the corrosive nature of the flue gas. As with the furnace tubes, superheater tube corrosion is also directly related to the outside metal temperature of the tube itself. This tube metal temperature is of course a function of the steam temperature and the flue gas temperature. To minimize the potential for corrosion, a parallel flow superheater design (Fig. 4) is used in the Westchester boiler design.

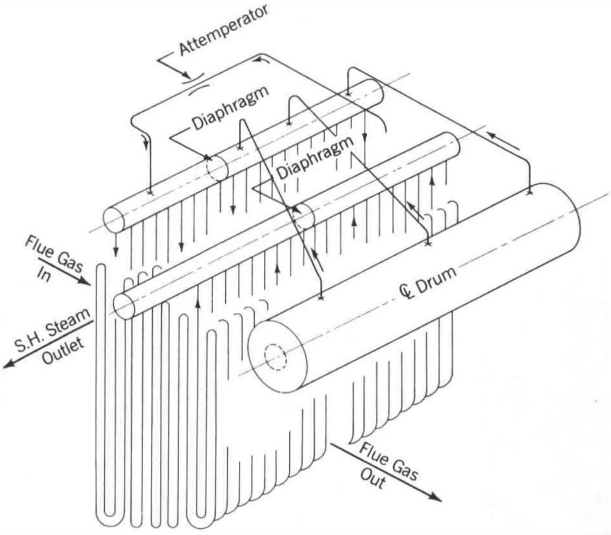
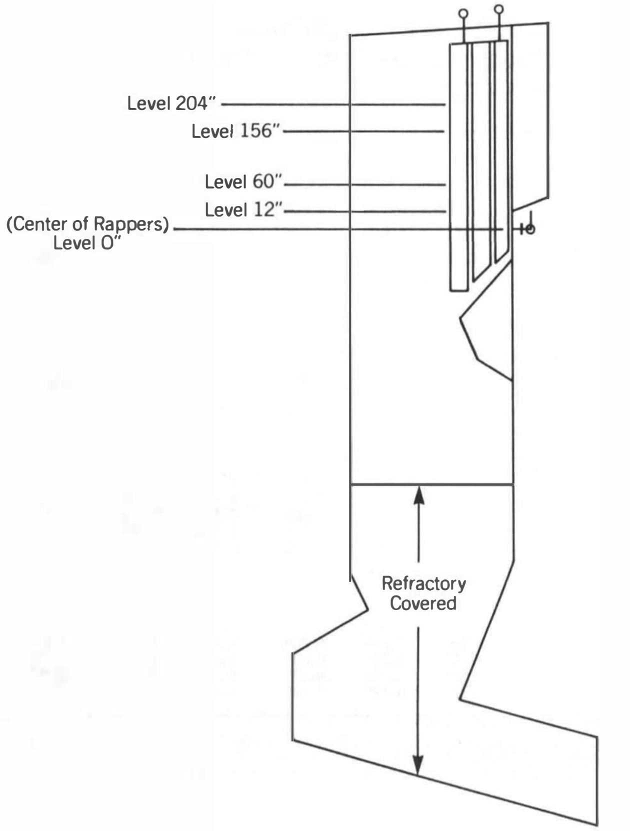


FIG. 4 PARALLEL FLOW SUPERHEATER



(Tubes are Numbered from Left to Right While Facing the Front Wall)

FIG. 5 IDENTIFICATION OF ULTRASONIC MEASUREMENT LOCATIONS AT SUPERHEATER FACE

In a parallel flow design, the steam and flue gas flow in the same, or parallel, direction - that is, the coolest steam inside the tube is in contact with the hottest flue gas outside the tube, and the hottest steam with the coolest flue gas — thus minimizing the occurrence of very high metal temperatures.

Even employing this conservative design, with the production of 830°F (443°C) steam, the resulting tube metal temperature in some of the tubes exceeds the metal use temperature limits of the carbon steel family. At the same time, most of the higher alloys typically used in high temperature superheater applications are not appropriate for use in the highly corrosive atmosphere of a refuse-fired boiler. The superheater metals chosen for the Westchester refuse boiler design are a combination of Inconel 825, SA 209 and SA 210 tubing.

In order to evaluate the superheater life, extensive ultrasonic tube thickness measurements have been taken on the Westchester boilers (location of measurements shown in Fig. 5). These data, shown in Table 3, indicate no significant metal wastage after three years and 22,000 hr of operating experience with an average flue gas entering temperature of approximately 1450°F (788°C). There has not been a single superheater tube failure in the Westchester boilers.

One means of protecting superheaters from the corrosive elements in the flue gas stream is to maintain a light layer of ash on the superheater tubes. For the Westchester boiler design, a mechanical rapping system (Fig. 6) was installed on the superheater which utilizes a hammer and anvil approach, adapted from precipitator rapping mechanisms, to impart a force which is transmitted to each superheater section. This mechanical shock is sufficient to prevent excessive fouling in the superheater, while leaving a slight layer of ash on the tubes. For lower temperature superheater designs, steam sootblowers with protective tube shields for the tubes adjacent to the sootblowers provide an appropriate cleaning system. However, for 830°F superheater designs, mechanical rapping is the preferred cleaning system to minimize corrosion potential.

BOILER AND ECONOMIZER

The boiler and economizer heating surface consists of long flow, shop assembled modules. The design is identical to proven modular designs used for many years in pulp and paper industry process recovery boil-

TABLE 3 WESTCHESTER SUPERHEATER
(Ultrasonic Tube Thickness Measurements)

	North		TUBE IDENTIFICATION			South
	#1	#10	#20	#30	#40	#51
Elevation 12"						
Operating Hours						
0	0.205	0.195	0.205	0.200	0.200	0.205
2,500	0.205	0.200	0.200	0.200	0.200	0.200
14,000	0.195	0.200	0.200	0.200	0.200	0.200
22,000	0.200	0.200	0.200	0.200	0.200	0.200
Elevation 60"						
Operating Hours						
0	0.205	0.210	0.210	0.215	0.205	0.200
2,500	0.200	0.200	0.200	0.200	0.200	0.200
14,000	0.200	0.200	0.200	0.200	0.200	0.200
22,000	0.200	0.200	0.200	0.205	0.200	0.200
Elevation 156"						
Operating Hours						
0	0.200	0.200	0.205	0.200	0.200	0.200
2,500	0.205	0.200	0.200	0.200	0.200	0.200
14,000	0.200	0.200	0.200	0.200	0.200	0.200
22,000	0.200	0.200	0.200	0.200	0.200	0.200
Elevation 204"						
Operating Hours						
0	0.195	0.200	0.200	0.210	0.200	0.205
2,500	0.205	0.210	0.205	0.210	0.210	0.205
14,000	0.195	0.195	0.195	0.200	0.195	0.200
22,000	0.195	0.195	0.195	0.200	0.195	0.200

Superheater tubes are 2.0 in. (50.8mm) 00, nominal 0.180 in. (4.6mm) wall thickness. Ultrasonic readings taken at face of leading tubes, scanning the tube, with the lowest reading in inches shown above.

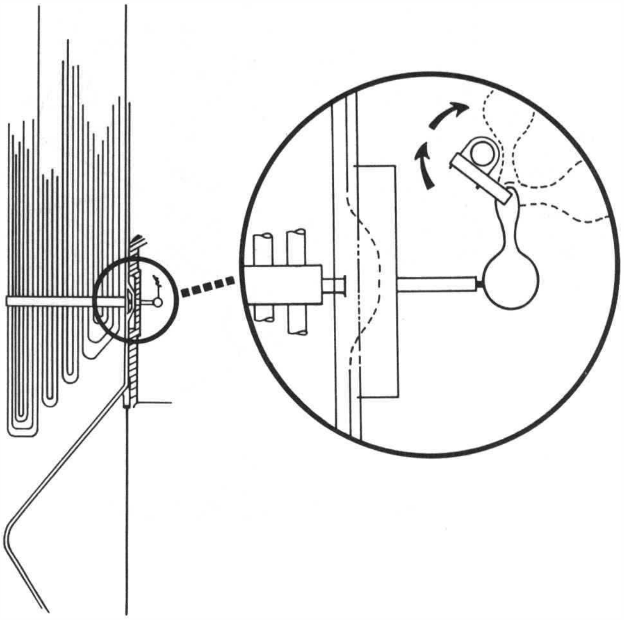


FIG. 6 SUPERHEATER MECHANICAL RAPPING SYSTEM

ers. In this design, the flue gas turns downward after exiting the superheater and flows parallel to the boiler module tubes, which utilize longitudinally extended surface similar to furnace membrane extended surface. This long flow design is very conservative and is well proven after hundreds of years of cumulative operating experience with the high-fouling flue gases from the burning of the black liquor residue in the paper making process.

Five stationary, extended lance sootblowers were installed along the length of the boiler module for ash removal from the tubes. Each lance has multiple sootblower nozzles positioned in line with the flue gas lanes between the tubes. The lance rotates 360 deg. to keep the entire lane ash free.

The only major problem area of the Westchester boiler design has been ash build-up at the upper portion of the boiler module. This ash build-up becomes significant enough to require complete shutdown of the boiler to clean the boiler module off-line. Such shutdowns have occurred approximately three times a year. While such shutdowns are undesirable from the viewpoint of maintenance cost and refuse throughput, the frequency of shutdowns has been incorporated into the

TABLE 4 WESTCHESTER REFUSE FACILITY
(Plant Performance Summary)

	1985	1986	1987
Refuse Processed*			
Tons	659,040	658,119	658,100
(t)	(597,749)	(596,414)	(596,897)
Time On-Line (%)	88.5	86.9	88.0
Throughput Availability* (%)	80.2	80.1	80.1
Ash/Fuel Ratio (%)	23.5	24.6	23.3
Steam Generated			
Mlbs	3,914,942	4,050,752	4,009,845
(t)	(1,775,426)	(1,837,016)	(1,818,464)
Net Power Sold			
Kwh/Ton	577	575	570
(kwh/t)	(636)	(634)	(628)

*Limited by Permit to 80% Availability.

TABLE 5 BALTIMORE REFUSE FACILITY
(Plant Performance Summary)

	1985	1986	1987
Refuse Processed			
Tons	684,565	724,516	724,436
(t)	(620,900)	(657,136)	(657,063)
Time On-Line (%)	87.2	92.7	94.1
Throughput Availability (%)	83.4	88.2	88.2
Ash/Fuel Ratio (%)	31.4	27.3	27.7
Steam Generated			
Mlbs	3,977,936	4,476,339	4,539,222
(t)	(1,803,994)	(2,030,020)	(2,058,537)
Steam Sold			
Mlbs	0	805,261	1,093,484
(t)	0	(365,186)	(495,895)
Net Power Sold			
Kwh/Ton	540	435	370
(kwh/t)	(595)	(480)	(408)

regular preventative maintenance program at the facility.

For the Millbury, Massachusetts refuse facility boilers, which are identical to the Westchester boilers in all other aspects, the spacing between the boiler module tubes was increased by 50% to lessen the potential for plugging. In lieu of steam sootblowers, a mechanical rapping system was installed on the boiler module similar to the mechanical rapping system proven to be effective in the superheater section. The Millbury facility went into commercial operation in September 1987.

CONCLUSION

Actual operating data (including refuse throughput, tons of refuse processed, ash/fuel ratio, etc.) for both the Westchester Refuse Facility and the Baltimore Refuse Facility are included in Table 4 and Table 5.

Based on the operating experience at the Westchester facility, as well as other mass refuse-fired plants, the following conclusions can be made:

(a) A large single pass furnace with a volumetric heat release rate in the range of 8000–10,000 Btu/ft^3-hr (215–268 kJ/m^3-h) has a proven operating record.

(b) The Westchester boilers have operated since March 1984 at 830°F (443°C) steam outlet temperature and 1450°F (788°C) gas temperature entering the superheater without any significant tube metal wastage.

(c) A superheater rapping system is an effective method of on-line cleaning high steam temperature superheaters since it efficiently clears the gas lanes without overcleaning the tubes.

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