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FURNACE/BOILER TEMPERATURE CORRELATION: MONTGOMERY COUNTY RESOURCE RECOVERY FACILITY 2 X 600 T/D PROCESS TRAINS

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INTRODUCTION

The Montgomery County, PA Resource Recovery Facility is a state-of-the-art waste to energy plant employing L&C Steinmüller combustion technology. A detailed description of this facility is presented in Reference 1.

As it is typical for such facilities, the operating permit issued to this facility imposed certain requirements in terms of combustion temperature, flue gas residence times and furnace preheating prior to the firing of waste. These requirements are aimed at the destruction of organics in the products of combustion. Some of the underlying reasons for this are presented in Reference 2.

To assure compliance with the conditions stipulated in the Temporary Operating Permit (TOP) for the Montgomery County facility, a furnace/boiler temperature correlation test was conducted on Boiler A (Figure 1). The purpose of the test was to identify a reliable temperature profile between the grate (primary combustion) and the economizer outlet over the full load range (0 to >100%) of the boiler, including preheating of the furnace via the oil burner.

To assure representation of normal operating conditions, the temperature correlation test was delayed until the completion of the acceptance test, or 10 weeks after boiler startup on MSW, to allow boiler fouling to take place.

The test started on a cold boiler with oil firing for furnace preheating and continued through a steam load on the boiler of 155,700 lbs/hr or about 106% load with solid waste fuel.

Permit Requirements

The temporary operating permit issued to the facility contained the following requirements regarding temperatures and residence time:

- The incinerator(s) shall maintain the combustion gases at a temperature greater than 1800°F for at least one (1) second. To verify compliance with this require ment, a temperature sensor shall be located at a position approved by the Department for each unit. The temperature at this location shall be maintained at a temperature greater than that which corresponds to the 1800°F/one (1) second requirement. The incinerator(s) auxiliary burners shall be automatically controlled to maintain the combustion gases at the aforementioned condition whenever refuse is being incinerated.
- Each incinerator shall be equipped with an automatic alarm and interlock system to stop the solid waste material charging grates if the following conditions occur:
  - The incinerator temperature measured above the DER approved location drops below a DER approved reference temperature (which corresponds to 1600°F) for a 15 minute period.
- Upon start-up of the incinerator(s), tests shall be conducted to demonstrate that the DER approved reference temperatures monitored by the sensor located at the DER approved location correspond to combustion gas temperatures of 1800°F and 1600°F respectively for

combustion gas retention times in each instance of one (1) second. Temperature monitor verification tests shall be performed during stack testing. The test plan required under Conditions of this T.O.P. shall also include procedures to assure compliance with the above temperature monitoring conditions.

- The incinerator(s) shall be equipped with test ports so that periodic measurement of the 1800°F/one (1) second residence time requirement can be conducted.
- In addition to the above, the following conditions were stipulated:
- Start-Up Requirements

  No solid waste shall be charged into the incinerator(s) until equilibrium has been attained in the furnace zones and the temperature of the combustion gases reaches 1800°F for 1 second of retention time. All control equipment shall be operational and functioning properly prior to the introduction of solid waste into the incinerator(s).
- Shutdown Requirements

  During the process of all planned shut downs of the incinerator(s), auxiliary burners shall be used to ensure that the temperature of the combustion gases do not drop below 1600°F while any waste material is still being incinerated. All control equipment shall be operational and functioning properly until all the solid waste is incinerated.

TEMPERATURE PROBE LOCATIONS

The temperature correlation test was executed by use of all permanent temperature probes in the boiler and was supplemented by readings from temporary probes installed specifically for this test into the furnace/boiler at various locations. The establishment of temperature levels at various locations in the boiler by means of permanent temperature instrumentation and supplemented by temporary temperature probes was deemed necessary to obtain a viable correlation of temperatures vs. load and flue gas residence times in the furnace. The following permanent probes were monitored during the test:

a. Short roof probe, left side of furnace
b. Short roof probe, right side of furnace
c. Superheater (convection sections) inlet probe
d. Economizer (boiler) outlet probe

See Figure 2 for actual locations of these probes.

The readings from the permanent probes were taken in the control room on the DCS-OIU (Digital Control System-Output/Input Unit). These readings were continuously available to the plant operator in the control room.

It should be noted that the center roof probe was replaced for testing purposes with a longer probe (10.5 feet vs. 7 feet), and is listed here as temporary test instrumentation. This longer probe was replaced again by a short probe and has become part of the furnace temperature surveillance system as required by the permit. Readings from this probe were also available in the control room on the OIU.

Temporary probes were used at the following locations (see Figures 1 and 2):

a. Water-cooled suction probe at burner level
b. Ardometer at furnace outlet
c. Water-cooled suction probe at furnace outlet
d. Long roof probe at center top of furnace
e. Thermocouple at superheater inlet
f. Thermocouple at economizer outlet

Probes a. through d. were required to establish a reliable temperature pattern in the furnace over the full load range in the gas stream. To this end suction probes were inserted 8.5 feet into the gas stream, approximately halfway into the furnace to alleviate the radiant cooling loss to the furnace walls. Equally, the superheater inlet probe was inserted 6.5 feet, again approximately halfway into the gas stream, versus about 3 feet for the permanent probe. The economizer probe was inserted 3 feet only into the gas stream, equal distance as the permanent probe, because the temperature at this location is relatively low. The purpose for these two probes was simply to obtain a reasonable measure of this cooling effect. The temporary probes were specifically fabricated for this test and inserted into fixtures attached to available openings in the furnace and boiler. The probes were made of 446 stainless steel. The thermocouple wire was of the K-type inserted into the thermocouples and shielded by ceramic in the suction probes. Readings were taken with General Electric digital thermometers with direct temperature display as adjusted for the thermocouple wire used. The Ardometer is a radiation pyrometer manufactured by Siemens A.G. This instrument is capable of accurately reading temperatures in a radiant heat environment. It was specifically set up and calibrated for measurements above 500°C (932°F) and high CO_2 atmosphere typical of MSW combustion. Therefore, during initial oil firing this instrument was not reliable because of the low temperatures and high excess air.

TEST PROGRAM

The test was planned to be executed after the completion of the Facility Acceptance Test to be assured that the boiler had sufficiently fouled during preceding operation and temperatures measured reflected actual normal operating conditions. To this end, all plant instrumentation was calibrated, temporary instrumentation was installed, and test personnel were available for complete coverage of all test stations on a continuous basis.

The temperature correlation test was executed on Boiler A, which had been shut down prior to the test to allow it to cool down to essentially ambient temperature.

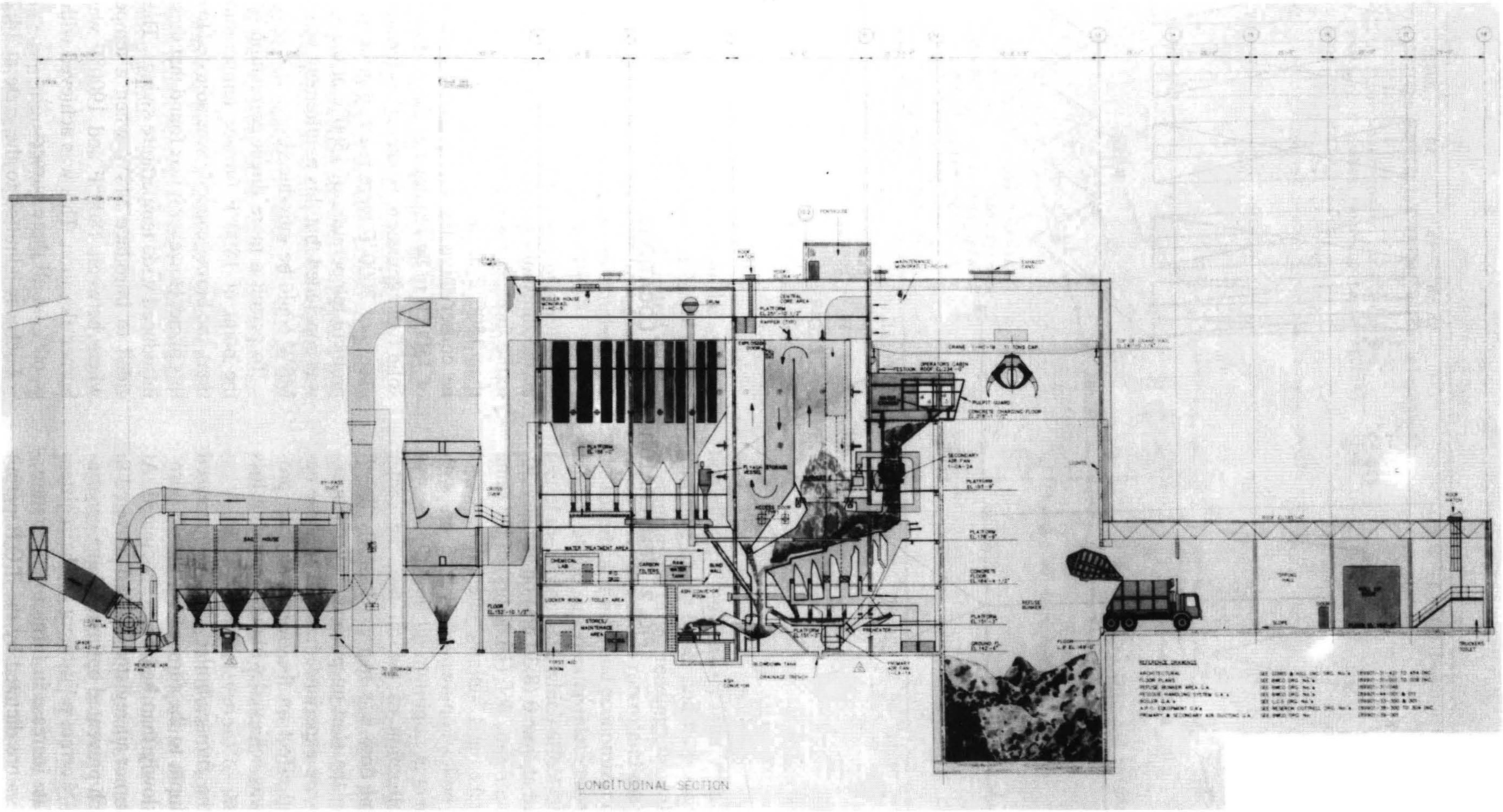


FIG. 1 FURNACE ELEVATION VS FURNACE TEMPERATURE (oF)

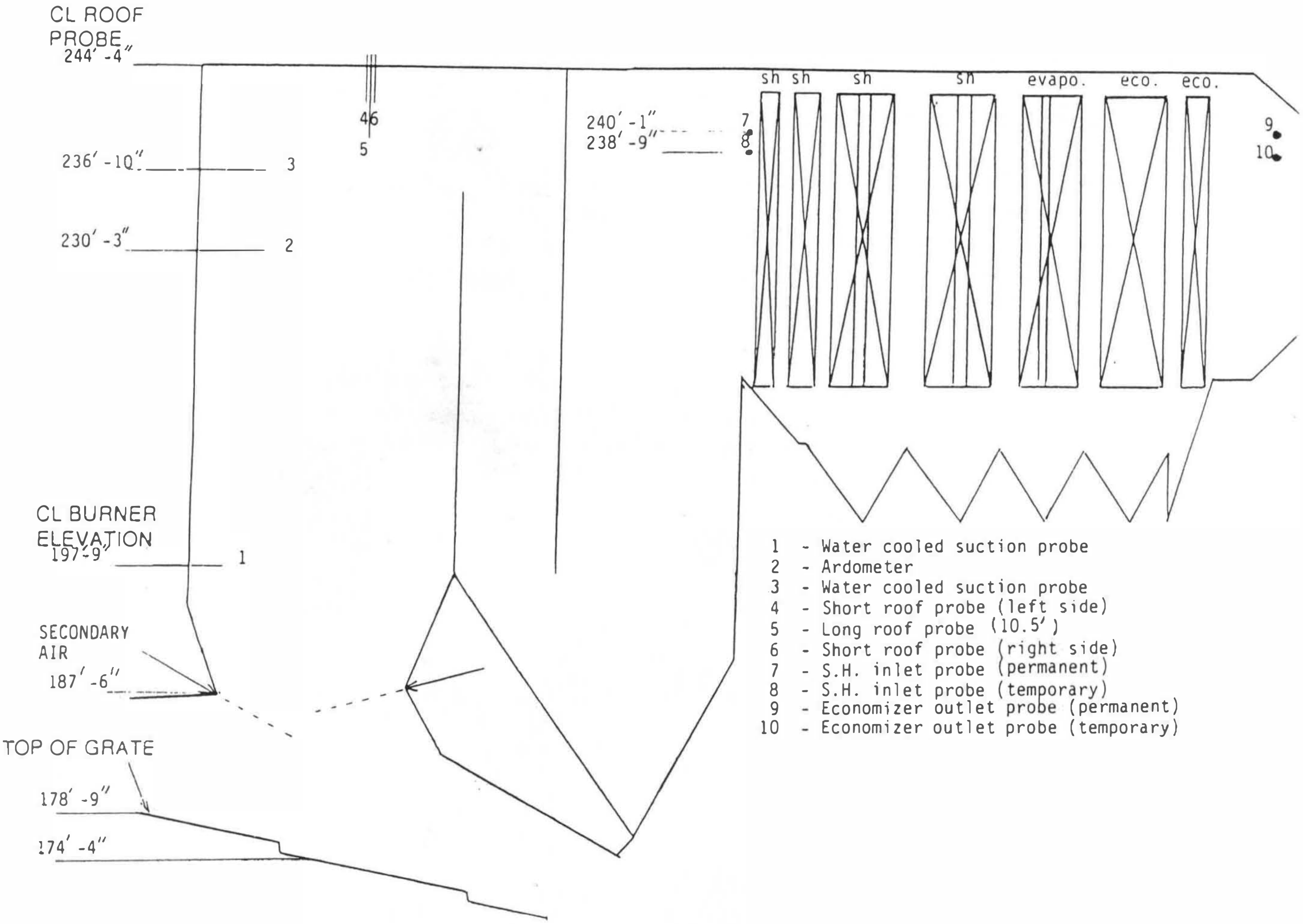


FIG. 2 TEMPERATURE PROBE LOCATIONS

The test was started at time 0 (8:30 hrs) on January 30, 1992 and continued until time 460 (16:00 hrs) of the same day. Readings were taken at 15-minute intervals.

Preheating of the boiler commenced at 8:53 hrs with the two outside burners at minimum oil flow (25% valve opening). After stabilization of the oil fire, the center burner was lit and oil flow was increased slowly on all three burners. During the start-up process, several unexplained burner trips were experienced; however, these occurrences had no real effect on the overall start-up program as re-ignition was achieved without significant loss in temperature levels.

Temperatures in the furnace/boiler steadily increased with increased heat input to the furnace via the oil burners, although more slowly than had been anticipated. At 12:30 hours the oil burner air registers were discovered to be set in a mode which prevented optimum flame penetration into the furnace. Correct adjustment of the registers produced an immediate increase in furnace temperature.

The 1800°F temperature dictated by the T.O.P. permit as the threshold temperature for the admission of MSW to the furnace was estimated prior to the test at much less than 1500°F at the optical probe location. Therefore, to be conservative the test protocol dictated a temperature of 1500°F to be obtained at the Ardometer level prior to solid fuel admission. However, as furnace temperatures in excess of 2000°F were reached prior to reaching the test protocol temperature of 1500°F at the Ardometer level, it was concluded that this requirement was too stringent and MSW could be introduced.

To permit a more direct correlation of temperatures at the point of 1800°F furnace temperature (burner elevation), the burner capacity was adjusted to obtain 1800°F at this plane. However it was found that these burner changes introduced wide temperature swings. Therefore it was decided to introduce MSW when a temperature of somewhere between 1800°F and 1900°F was reached at the burner elevation. This was achieved with a burner setting of 60% on all three burners.

Fuel was admitted to the grate at 14:23 hours without

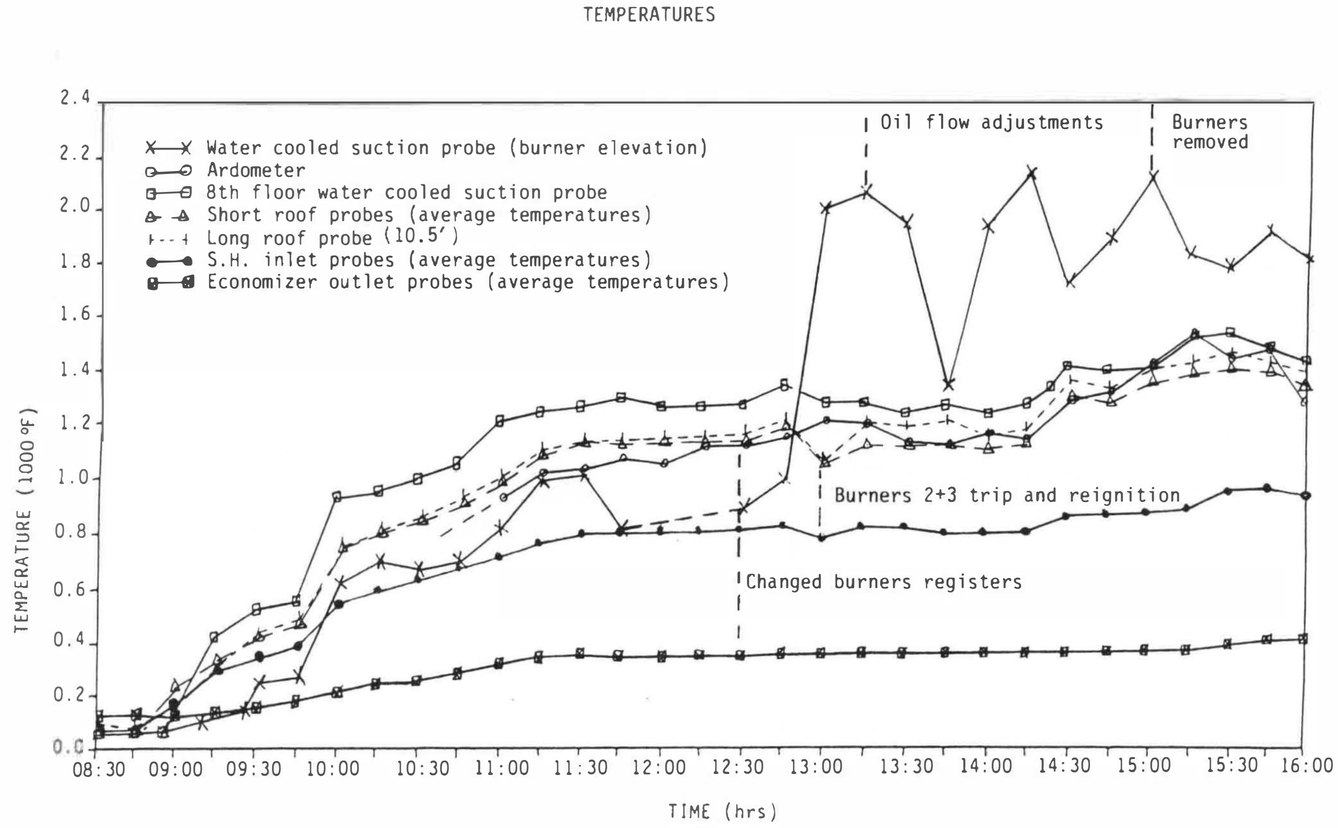


FIG. 3 TEMPERATURES

any significant effect on the temperatures in the system. Ignition and combustion of the first load of MSW on the grate was manipulated by introduction and control of primary air to the first grate zone. Ignition took place essentially immediately and gas temperatures climbed and steam flow increased to 116,600 lbs/hr or 79%.

Oil burners were sequentially taken out of service between 15:07 hours and 15:30 hours and sole MSW combustion was in effect at 15:30 hours. At that point, the test was deemed complete and steam flow was regulated to MCR conditions.

During the initial preheating period, the boiler steam flow measurements were not reliable because of initial, and later continuous, venting of the convection section, as well as draining of the convection sections to relieve water swell. As drum pressure increased and positive steam flow was established at higher heat input levels, the drains and vents were closed and reliable steam flow measurements were obtained.

Oil flows were obtained from oil pressure measurements in the oil supply and return headers by means of the manufacturers correlation graph.

TEST DATA

Actual test data taken at the various locations have been plotted against time on Figure 3. This graphic presentation allows a much easier interpretation of the actual performance of the boiler and its permit related parameters. A comparison of the readings from the permanent probes (DCS-OIU in control room) and the temporary probes at the superheater inlet and economizer outlet indicated a difference at the superheater inlet caused by the cooling effect of the water wall, which affects the shorter permanent probe to a larger degree. At the economizer outlet, where no cooling takes place, both the permanent and temporary probes read essentially the same temperature. The test data also indicated some temperature difference between the two permanent short roof probes, which apparently was caused by some minor gas flow maldistribution. As the difference between the right and left furnace side is essentially negligible, the data evaluation was based upon the average reading between the two probes.

A cursory review of the raw data indicated a very good correlation of the temperatures across the gas pass from the furnace (burner elevation) to the economizer outlet. This indication is even more obvious by review of Figure 3, which shows the composite of all measured temperatures over the test duration. Other data taken during the test and required for this analysis are steam flow, primary and secondary air flows, and fuel oil flows. These data are graphically presented in Figure 4. MSW feed rates are not readily available for a short time test and therefore were backed out from the steam flow data by use of an average

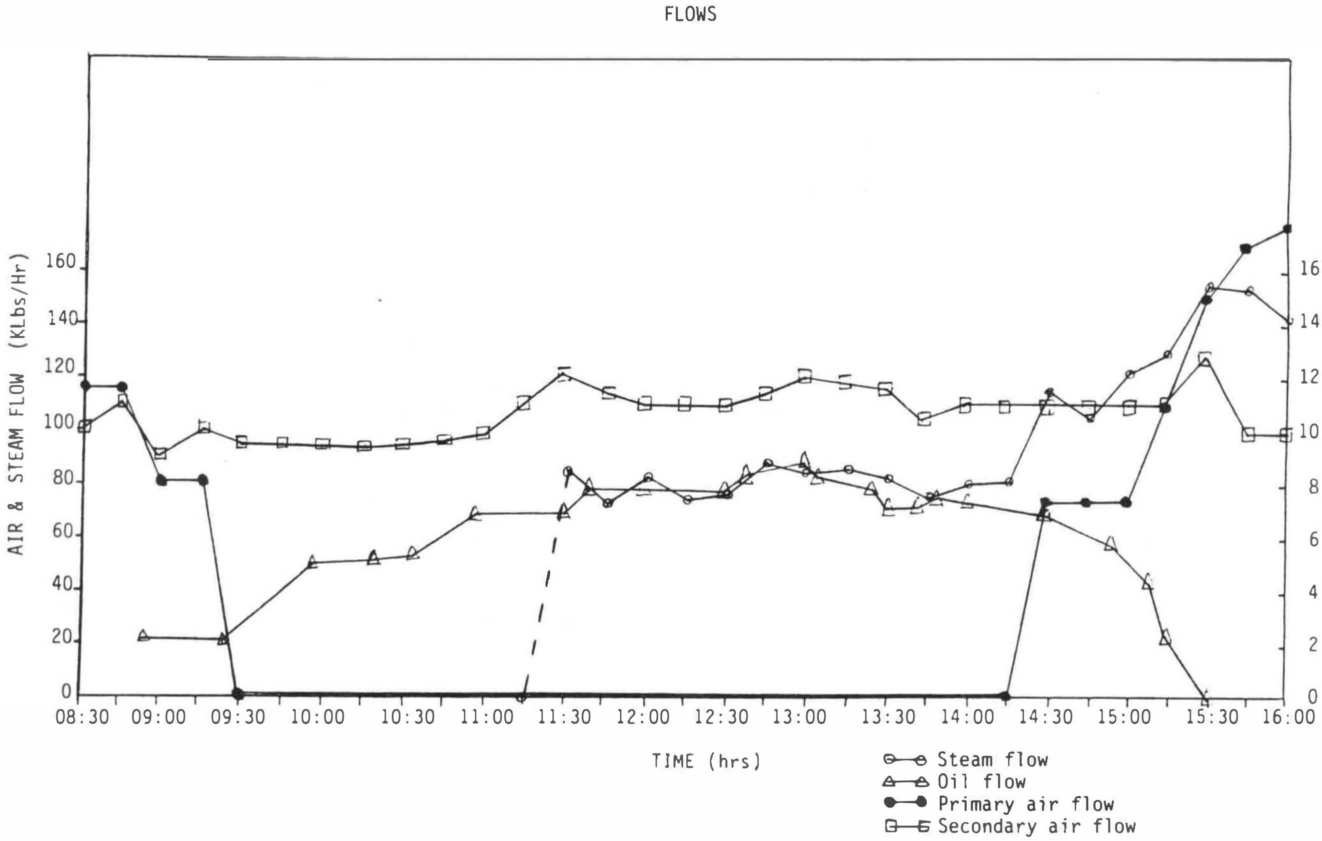


FIG. 4 FLOWS

fuel higher heating value as obtained from the preceding Facility Acceptance Test.

DATA REDUCTION

To permit an easy and practical utilization of the actual test data for plant operation, the data needed to be reduced to a set of curves which represent a theoretical load progression from cold start-up to peak load. Thus the effects of minor system upsets, as occurred during the test, such as burner trips and restarts, MSW quantity and quality fluctuations, etc. were eliminated. Although such disturbances to the hypothetical temperature progression will typically occur during normal plant operation, they need not be considered in the context of this correlation.

Figure 3 depicts a temperature composite for measurements taken at the burner level, the furnace exit (Ardometer), top of the first radiant pass (suction probe in right side wall, temporary long roof probe and permanent short roof probes), the superheater inlet and the economizer outlet over time. In order to relate this composite to the boiler load, it was compared to the steam flow measurements taken during the test, as presented in Figure 4. Real steam flow measurements were obtained at 11:30 hours for the first time during the test, after all vents and drains were closed on the boiler. Combining Figures 3 and 4 results in a temperature-load chart over the full operating range of the boiler (Figure 5). Here it was assumed that the steam load, which is a function of temperature and mass flow of the combustion gas, would steadily increase with fuel flow, and fuel heating value and excess air would be constant. It should be noted that the temperature at the prescribed control point, namely the roof temperature, is only a function of the total heat input into the furnace, whether it be oil or MSW supplied, or a combination of both fuels. To obtain a real temperature progression from cold start-up on oil to the point of MSW admission, the temperatures as measured during the initial phase of the test at the burner elevation were replaced by a steady temperature progression, as it would have taken place with the correct burner register setting. This approach can be considered valid as this temperature profile now matches the temperature profiles of the other test locations. Furthermore, the actual progression of the heat-up in the furnace is of little interest as far as the permit requirement is concerned. The only point of interest is the point at which a temperature of 1800°F has been reached in the furnace, so that MSW can be charged.

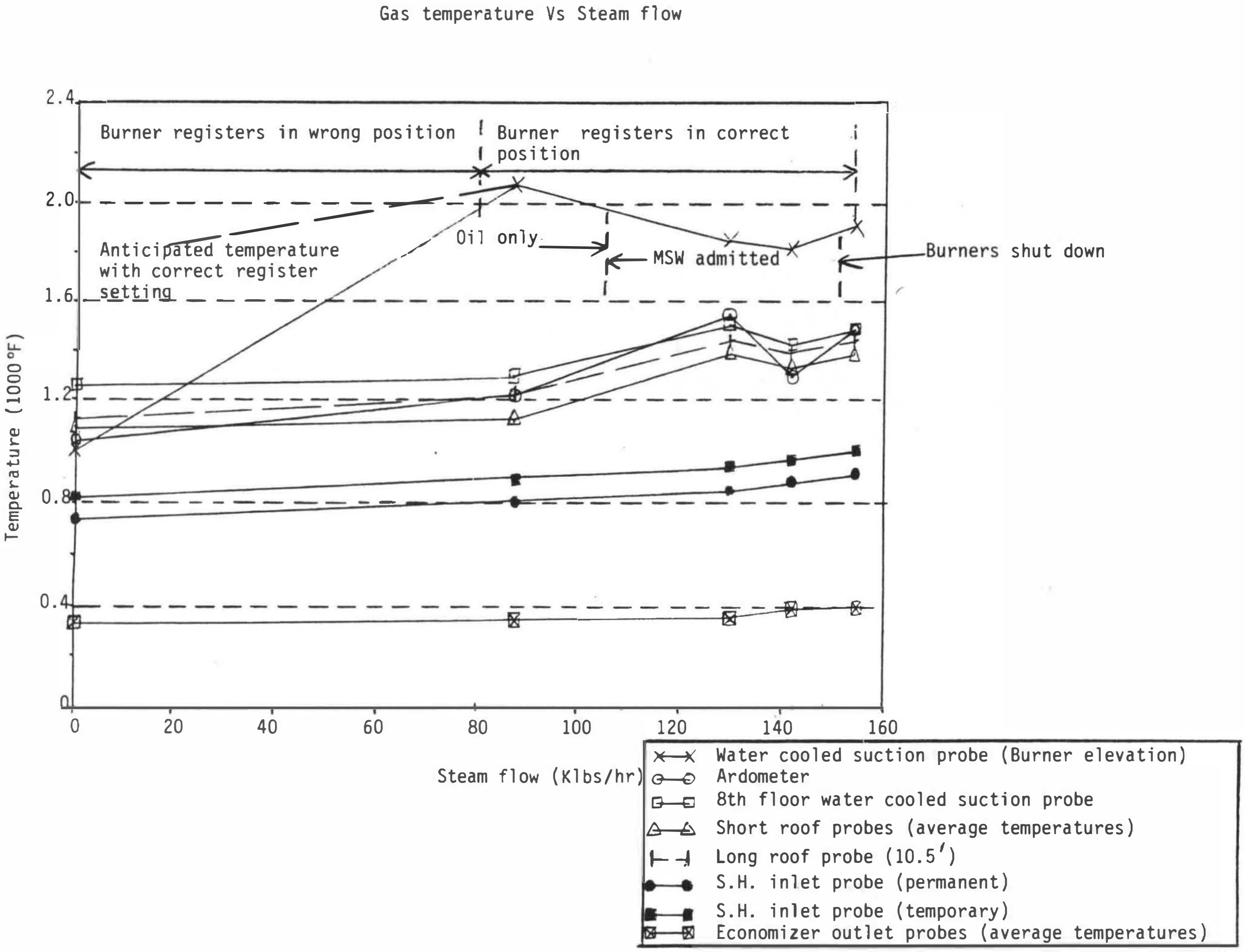


FIG. 5 GAS TEMPERATURE VS STEAM FLOW

ADIABATIC FLAME (FLAME TIP) TEMPERATURE

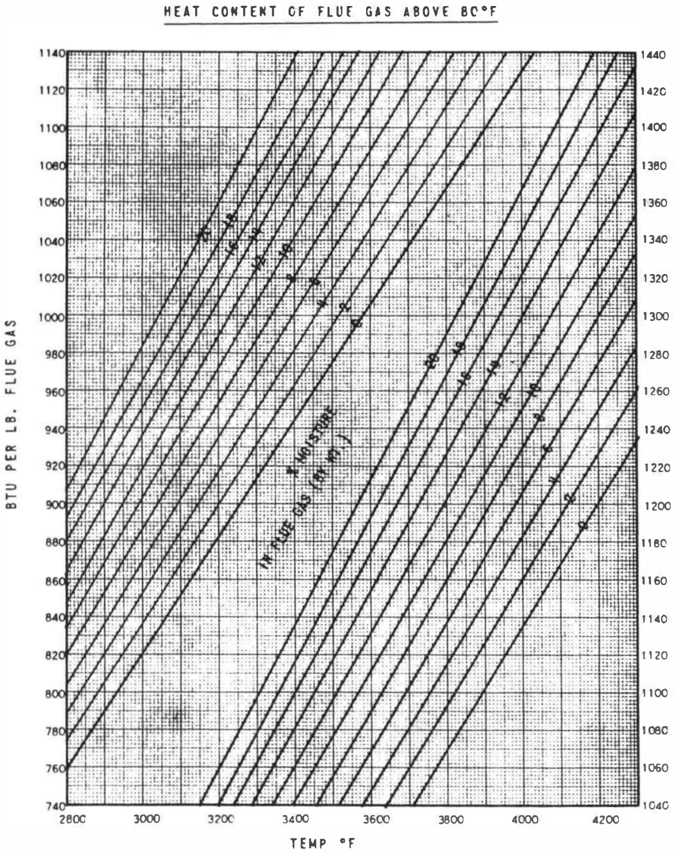
To permit an evaluation of the temperature level in the furnace, the adiabatic temperature was determined for oil firing from Figure 6 at various points in the start-up test program based upon the actual oil flow data and the actual combustion air (secondary air) consumption. The moisture in the flue gas during oil firing has been obtained from the continuous emission monitoring system (CEMS).

The determination of the flame tip temperature in the furnace under MSW combustion conditions was executed on the same basis from Figure 6.

As MSW combustion takes place at two levels, e.g. solids on the grate and volatiles in the secondary air zone, the whole lower furnace is filled with flames. This can be documented by actual boiler observation, either directly or via the combustion surveillance system (TV-cameras).

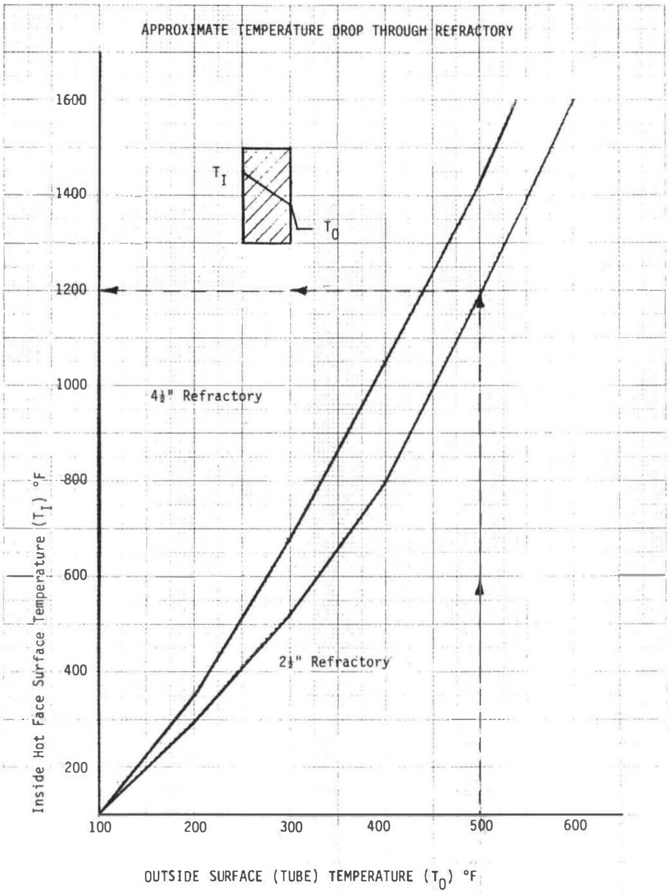
The secondary combustion zone extends reasonably well above the elevation of the secondary air injection nozzles, therefore a conservative assumption can be made that the flame front and therefore the flame temperature extends at least up to the secondary air injection elevation under normal MSW combustion conditions which were defined for this particular boiler at 85% excess air and a 60/40% split between primary and secondary air.

As indicated earlier, the MSW firing rate was determined from the steam flow (total heat input) as based upon an reasonable average heating value derived from the Facility Acceptance Test. The flue gas moisture component, as determined by the emission control system during the temperature test, was used for this calculation as these instruments had been certified. The flue gas flow was based upon the primary air flow plus the total amount of the MSW supplied less its ash content, for the primary com-



Reference: Riley Stoker Corp., Worcester, MA, (1958)

FIG. 6 HEAT CONTENT OF FLUE GAS ABOVE 80°F



Reference: Bigelow-Liptak Corp., Detroit, MI (1951)

FIG. 7 APPROXIMATE TEMPERATURE DROP THROUGH REFRACTORY

bustion zone, grate to secondary air level. The ash content was based upon Facility Acceptance Test data. For the remainder of the system, e.g. secondary air level to boiler exit, the amount of secondary air was added to the flue gas flow as determined for the primary combustion zone.

Although the adiabatic temperature for oil firing is theoretically a constant, fluctuations in excess air and flue gas moisture will have a minor effect on this temperature. Therefore it has been calculated for several conditions in the range of interest, which is where the furnace temperature has reached the 1800°F temperature requirement for admission of solid waste fuel. It is known from experience (tests conducted at the Southeast Resource Recovery Facility, Warren County Resource Recovery Facility and Hennepin County Resource Recovery Facility) that this temperature correlates approximately with a roof temperature in the furnace of 1000°F to 1200°F, depending on the length of the thermocouples in use and the associated effect of cooling from the boiler roof tubes:

Three representative data points were selected from Figure 3 and Figure 4 and compared to the flame temperature as obtained from Figure 6 (Table 1):

TABLE 1 TEMPERATURE AT FLAME TIP

Time	Steam Flow lbs/hr	Roof Temperature °F	Temperature Burner Elevation °F	Flame Tip Temperature °F
13:00	86,300	1062.5	2000	~ 4000
14:00	81,400	1115.0	1950	~ 3850
14:15	81,900	1135.5	2145	~ 3800

ANALYSIS OF FURNACE TEMPERATURE

It should be realized that because of the initial wrong burner register settings, the boiler was overfired with oil in order to achieve the 1800°F furnace temperature. When the burner registers were set correctly, the furnace temperature was actually higher than would have been required to achieve a furnace temperature of 1800°F. Therefore several burner adjustments were attempted to stabilize the fur-

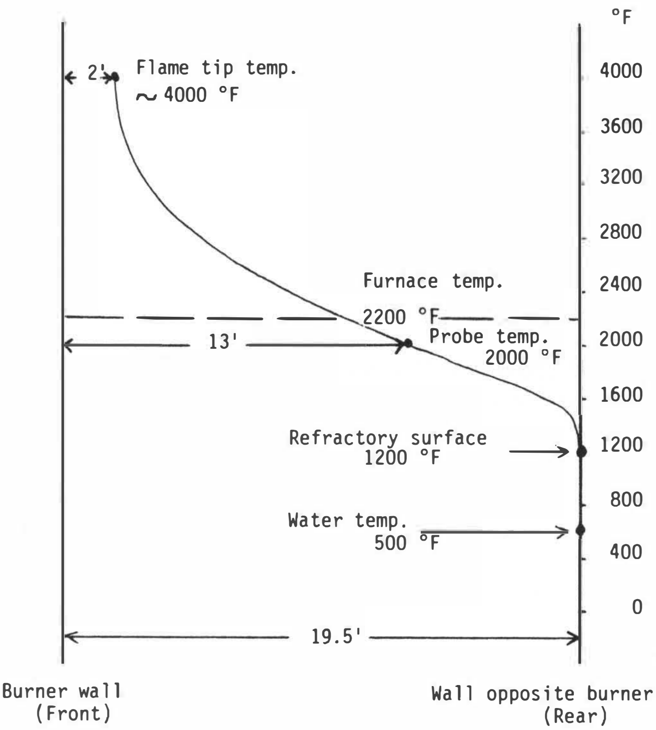


FIG. 8a TEMPERATURE DISTRIBUTION IN FURNACE DURING OIL FIRING CASE 1—ROOF TEMPERATURE: 1062°F

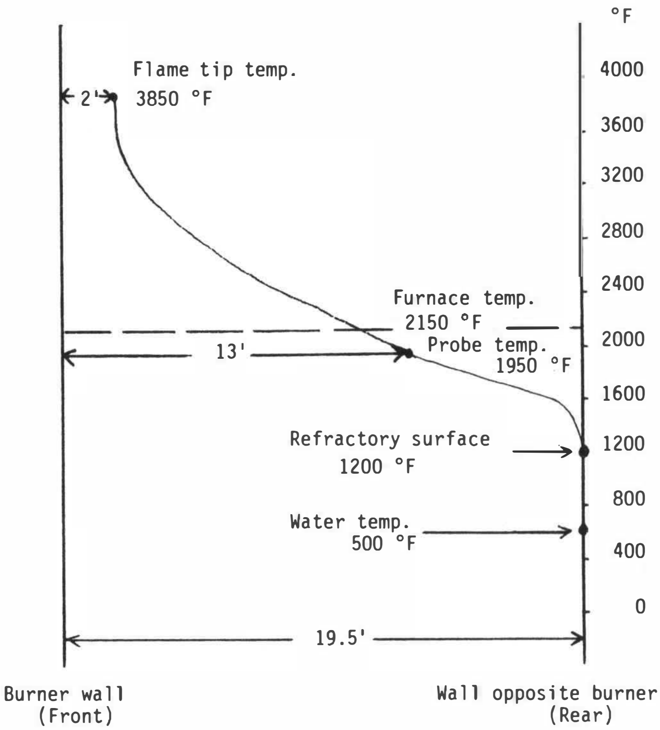


FIG. 8b TEMPERATURE DISTRIBUTION IN FURNACE DURING OIL FIRING CASE 2—ROOF TEMPERATURE: 1115°F

nace at 1800°F; however, this proved to be difficult, as the furnace temperature reacted very quickly to a change in burner setting. Therefore, the furnace temperature analysis was based upon the selection of the above three points in time, which occurred after the burner had been set correctly.

The furnace is covered with refractory of about $2\frac{1}{2}$ inch in thickness which retains heat. The hot face temperature of the refractory-covered furnace wall can be estimated for a tube temperature of approximately 500°F corresponding to a drum pressure of about 750 psig from Figure 1. A graphic analysis was then used to present the temperature distribution in the furnace from the flame temperature (hottest) to the rear wall temperature (coldest) for the three different conditions shown. This analysis is presented in Figures 8a through 8c with the refractory surface temperature estimated at 1200°F. The results of this analysis are presented as a function of the roof temperature in Figure 9, which indicates that the permit requirements of 1800°F furnace temperature for admission of MSW to the grate is very conservatively fulfilled after a roof temperature of 1000°F has been obtained.

As a matter of fact, inspection and interpolation of the temperature profiles presented in Figures 6a through 6c indicate that a roof temperature lower than 1000°F would probably have been sufficient to assure that a furnace temperature of 1800°F has been obtained.

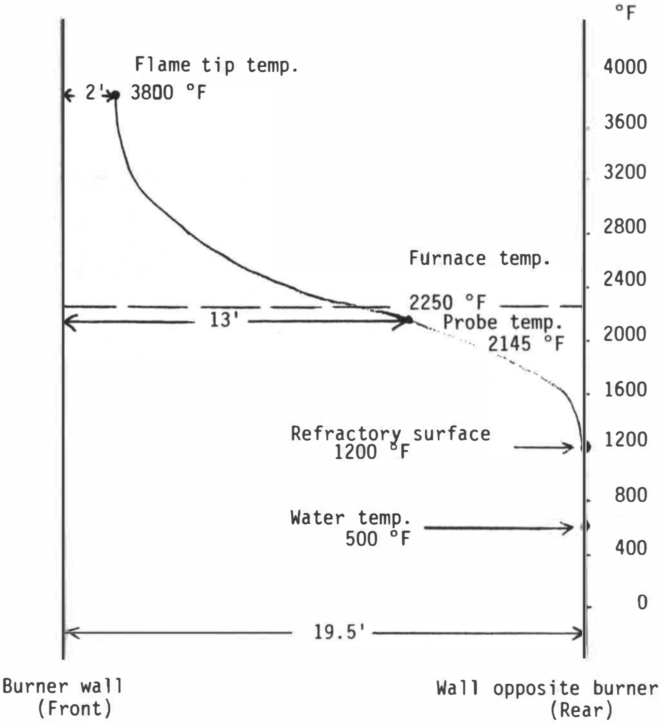


FIG. 8c TEMPERATURE DISTRIBUTION IN FURNACE DURING OIL FIRING CASE 3—ROOF TEMPERATURE: 1135°F

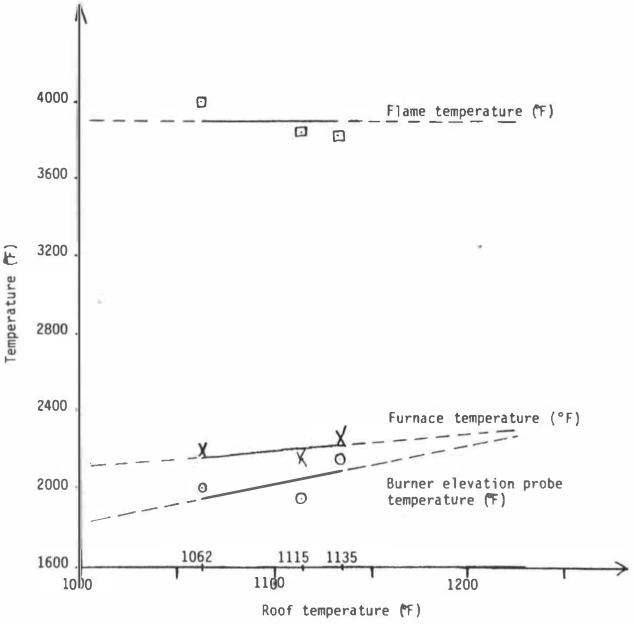


FIG. 9 FURNACE TEMPERATURE DURING OIL PREHEATING

FURNACE TEMPERATURE DURING MSW FIRING

The determination of the flame temperature for MSW firing at full load operation was based on actual data obtained during the Acceptance Test of the facility for the MSW heating value and ash values (amount and C-content).

Average Higher Heating value of as-fired MSW during Facility Acceptance Test	5502 Btu/lb
Heat loss due to combustibles in residue	128 Btu/lb
Total residue (dry)	21%
Effective Higher Heating Value of Fuel	5475 Btu/lb

Temperature Test Conditions (15:45 hours)

Steam Flow:	154, 200 lbs/hr
Percent of full load:	105%
Primary Air Flow:	170, 100 lbs/hr
Secondary Air Flow:	100, 900 lbs/hr
Total Air Flow:	271, 000 lbs/hr
Heat input:	1.05 × 253, 530, 000 = 266, 206, 500 Btu/hr
MSW Firing Rate at 5475 Btu/lb (combusted plus non-combusted at 128 Btu/lb):	48, 622 lbs/hr
Gas Flow Rate:	309, 411 lbs/hr
Flue Gas Moisture	13%
Total Heat in Flue Gas:	860 Btu/lb
Adiabatic temperature (Flame tip):	2800°F

From this calculation it is proven that the adiabatic temperature for MSW-firing is much lower than for oil-firing, however during oil firing, the flame does not fill the whole furnace as is the case with MSW firing. During MSW firing the flame temperature will be constant unless MSW composition (inert content), heating value and/or the amount of combustion air (excess air) changes significantly, a situation which is not anticipated during normal facility operation.

However, actual load and gas weight will have an effect on the location of the flame, which moves up in the furnace with increasing load. Therefore, the flame temperature, calculated to be 2800°F, may be at a higher elevation than the secondary air injection level under high load conditions.

As a reasonable approximation, it can be assumed that a linear temperature profile exists from the secondary air injection level to the roof probe level (see also calculated profile in Figure 10). The furnace is partially refractory lined and the low absorptivity of the refractory material dampens the normal exponential temperature relationship. This is also true for slag covering the furnace walls.

This linear profile is defined by the temperatures between the adiabatic temperature at the secondary air level and the roof probes.

After prewarming the furnace and upon admission of MSW, the oil burners will stay in service until stable MSW combustion is achieved. During dual firing, the adiabatic flame temperature will fall somewhere between 3800°F (oil only) and 2800°F (MSW only).

GAS RESIDENCE TIMES

The gas residence time during MSW combustion was determined for full load based upon the adiabatic temperature calculated, the temperature measured at the burner elevation and the roof probe temperature. Assuming a normal load/temperature progression during the start-up process on MSW without the benefit of oil-preheat and stabilization, a temperature distribution can conservatively be assumed for load points below full load and residence

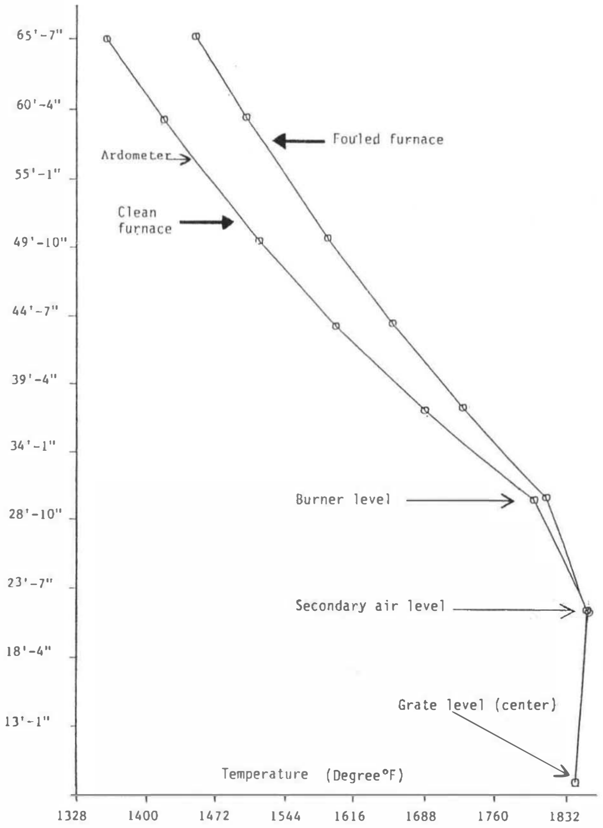


FIG. 10 FURNACE TEMPERATURES VS. HEIGHT

TABLE 2 GAS RESIDENCE TIMES

Time	Heat Input %	Adiabatic Temperature °F	Roof Temperature °F	Residence Times Seconds
15:45	105	2800°F	1411	4.1
11:30	50	2800°F	1145	7.7
9:55	35	2800°F	752	9.5

times above 1800°F can be calculated for the gas flow, as was done for 35% and 50% steam load (Table 2).

From these calculations it can be proven that the 1800°F/1 second permit requirement will be fulfilled with MSW-heat input alone to satisfy any load in the boiler beyond oil startup.

Under actual start-up conditions, where oil stabilization replaces a portion of the MSW heat input, the total air flow requirement is reduced, resulting in a lower gas velocity, while simultaneously increasing the furnace temperature because of the higher adiabatic oil temperature at the burner level. Therefore, the calculations as to residence times at 1800°F during initial MSW firing are very conservative.

Gas velocity calculations were based upon an average gas temperature and an average gas flow area under consideration of the actual geometries involved.

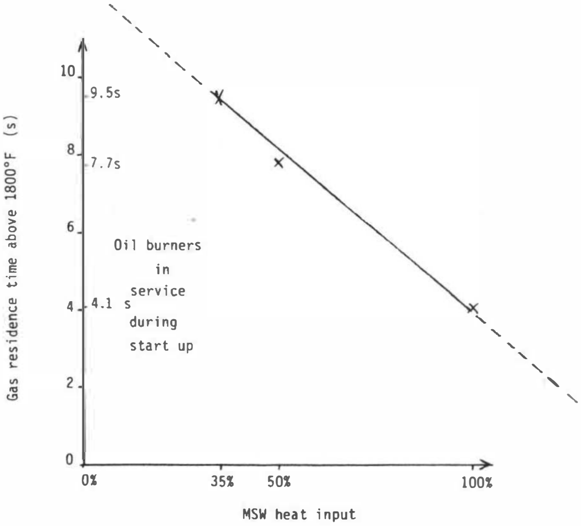


FIG. 11 GAS RESIDENCE TIME ABOVE 1800°F VS MSW HEAT INPUT

The results of the gas residence times study are depicted on Figure 11. A sample calculation is included in the Appendix.

MINIMUM OPERATING CRITERIA

From the test data obtained during the furnace/boiler temperature correlation test and their analysis, the following operating guidelines were established to comply with permit requirements.

Cold Start-Up

Boiler start-up shall commence with oil burners on minimum oil flow. Increase oil flow equally on burners until a furnace roof temperature of 1000°F is attained. The furnace roof temperature shall be measured by the short roof probes (permanent probes). If the probe temperatures signals are averaged, the average of at least two probes shall be available and shall be at 1000°F. If signals are not averaged, at least two probe temperatures shall be available and read 1000°F.

Under emergencies, e.g., two failed probes, reliance may be placed upon the last operating probe. However, every effort shall be made to replace failed roof temperature thermocouples.

When the relevant roof probe temperature indicates 1000°F, MSW may be admitted to the grate. The 1000°F roof temperature during oil preheating of the furnace relates to a furnace temperature of about 2100°F, or 300°F above the permit requirement. This margin is sufficient to guard against any deviations from a normal start-up condition which may have an effect on this temperature.

Load Increase on MSW

Increase MSW fuel feed as required to achieve desired load increase. Maintain oil firing at same burner setting as maintained prior to MSW introduction. Observe roof temperature and attain 1100°F. When 1100°F roof temperature is reached, reduce oil flow slowly to minimum on all burners and remove burners from service sequentially. As shown by the gas residence time calculations, the 1800°F/1 second permit requirement is fulfilled at any MSW only heat input. Therefore, the roof temperature of 1100°F is deemed to be a very safe limit for an indication of sufficient time at temperature for MSW operations, and after reaching this temperature burners may be taken out of service.

Shut-down

As load is decreased in anticipation of a shut-down, oil burners shall be put into service when the roof temperature approaches 1000°F under MSW firing conditions. Oil flow shall be increased gradually with decreasing heat input from the MSW to maintain between 900°F and 1000°F roof temperature. Oil burners may be taken out of service when the MSW fire is extinct.

Temperature Stabilization

As the 1800°F/1 second permit requirement is fulfilled with MSW combustion at all load levels above oil preheating/start-up, no temperature stabilization via oil firing is required during normal MSW operation, other than during start-up and shut-down of a boiler.

Temperature Probe Failure

In the rare event that all three roof temperature probes should have failed simultaneously, the superheater inlet probe shall be used for temperature monitoring. The temperature at this probe shall be 800°F prior to MSW admission. During MSW combustion the superheater inlet probe shall be maintained at 800°F minimum.

REFERENCES

[1] Randolph Bayer, Yoon Chae, Jay Lehr, and Wolfram Schuetzenduebel "Operating Experience — Montgomery County PA, Resource Recovery Facility" ASME — National Waste Processing Conference, Boston, Mass., June 1994.

[2] William Nobles, Janine Kelly, and Wolfram Schuetzenduebel "The Determination of Furnace Temperature Operating Criteria for Compliance with the Hennepin County Resource Recovery Facility's Air and Solid Waste Permit". Proceedings, Sixth International Conference on Solid Waste Management and Materials, Philadelphia, PA, December, 1990.

APPENDIX

Determination of Gas Residence Times: Sample Calculation

Approximately 100% Heat Input (MSW only).

105% Heat Input at 15:45 hours

Adiabatic Temperature:	2800°F
Roof Tube Temperature (Avg.):	1411°F
Total Gas Flow (above secondary air):	309,411 lbs/hr
Total Gas Flow (below secondary air):	208,511 lbs/hr
Gas Residence Time Above 1800°F:	R=4.1s

Calculation of R

R: Gas Residence Time Above 1800°F

$$R = \frac{\Delta E_1}{V_1} + \frac{\Delta E_2}{V_2} + \frac{\Delta E_3}{V_3} \quad (s)$$

ΔE_1(Ft):	Elevation difference between the Secondary Air Level (S.A.L.) and the center of the grate (Figure 2).
V_1(Ft/s):	Average Gas Velocity between the center of the grate and the S.A.L.
ΔE_2(Ft):	Elevation difference between the E and the S.A.L.
V_2(Ft/s):	Average Gas Velocity between the S.A.L. and the level E.
ΔE_3 (Ft):	Elevation difference between the level at which the temperature is 1800°F (E_{1800}) and E.
V_3 (Ft/s):	Average Gas Velocity between E and E_{1800}.

$$R = \frac{\Delta E_1}{V_1} + \frac{\Delta E_2}{V_2} + \frac{\Delta E_3}{V_3}$$

$$<=> R = \frac{187.5' - 174.3'}{V_1} + \frac{191.5' - 187.5'}{V_2} + \frac{E_{1800} - 191.5'}{V_3} \quad (1)$$

$$<=> \boxed{R = \frac{13.2'}{V_1} + \frac{4'}{V_2} + \frac{E_{1800} - 191.5'}{V_3}}$$

I. Calculation of E_{1800} (Elevation at which the temperature is 1800°F)
See Figure A.

Elevation	S.A.L: 187,5'	Roof Probe: 237,3'	E_{1800}?
Temperature	2800°F	1411°F	1800°F

$$\rightarrow \frac{2800 - 1411}{237.3' - 187.5'} = \frac{2800 - 1800}{E_{1800} - 187.5'}$$

Hence:

$$E_{1800} = \frac{1000}{1389} \times 49.8' + 187.5'$$

$$\boxed{E_{1800} = 223.4'}$$

II. **Calculation of V_1**

$$V_1 = \frac{Q_1}{S_1} \quad (Ft./s)$$

Q_1 (Ft.^{3}/s):	Gas flow from the grate to the S.A.L.
S_1 (Ft.^{2}):	Section 1 (Flow area, lower furnace).

$S_1 = 28.7' \times 21.6'$ (21.6' is the boiler width)

$S_1 = 619.9 \text{ Ft.}^2$

$$Q_1 = \underset{(Lbs/s)}{\frac{Q_{W1}}{3600}} \times \underset{(Ft^3/lb)}{X}$$

With $Q_{W1} = 208,511$ Lbs/Hr.

Flue Gas 10% water by weight (at one atmosphere and 1000°R)	25.7 Ft³/Lb
Same at one atmosphere and 2800°F	25.7 x $\frac{(2800 + 460)}{1000}$

Hence $X = 25.7 \times \frac{(2800 + 460)}{1000}$

X = 83.8 Ft.³/Lb. (at 2800°F)

So $Q_1 = \frac{208{,}511}{3600} \times 83.8$

Q_1 = 4853.7 Ft.³/s

Hence $V_1 = \frac{Q_1}{S_1}$

$V_1 = \frac{4853.7}{619.9}$

$$\boxed{V_1 = 7.8 \text{ Ft./s}}$$

III. **Calculation of V_2**

$V_2 = \frac{Q_2}{S_2}$ (Ft./s)

Q_2 (Ft.³/s) : Gas Flow from the S.A.L. to E

S_2 : Section 2 (Flow area, constriction)

S_2 = 13.0' x 21.6'

S_2 = 280.8 Ft.²

$Q_2 = \frac{Q_{w2}}{3600} \times Y$

(Lbs/s) (Ft.³/Lb)

With Q_{w2} = 309,411 Lbs/Hr.

Flue Gas 10% water by weight at one atmosphere and at $\frac{2800 + 1800}{2}$ = 2300°F	25.7 x $\frac{(2300 + 460)}{1000}$

Hence $Y = 25.7 \times \frac{(2300 + 460)}{1000}$

Y = 70.9 Ft.³/Lb. (at 2300°F)

So $Q_2 = \frac{309{,}411}{3600} \times 70.9$

Q_2 = 6093.7 Ft.³/s

Hence $V_2 = \frac{Q_2}{S_2}$

$V_2 = \frac{6093.7}{280.8}$

$$\boxed{V_2 = 21.7 \text{ Ft./s}}$$

IV. **Calculation of V_3**

$V_3 = \frac{Q_2}{S_3}$ (Ft./s)

With $Q_3 = Q_2$ = 6093.7 Ft.³/s

S_3 = Section 3 (Flow area, upper furnace)

S_3 = 19.5' x 21.6'

S_3 = 421.2 Ft.²

$V_3 = \frac{Q_3}{S_3}$

Hence $V_3 = \frac{6093.7}{421.2}$

$$\boxed{V_3 = 14.5 \text{ Ft/s}}$$

V. **Gas Residence Time Above 1800°F**

(1) $R = \frac{13.2'}{V_1} + \frac{4'}{V_2} + \frac{E_{1800} - 191.5'}{V_3}$

$R = \frac{13.2'}{7.8} + \frac{4'}{21.7} \quad \frac{223.4' - 191.5'}{14.5}$

$$\boxed{R = 4.1 \text{ s}}$$

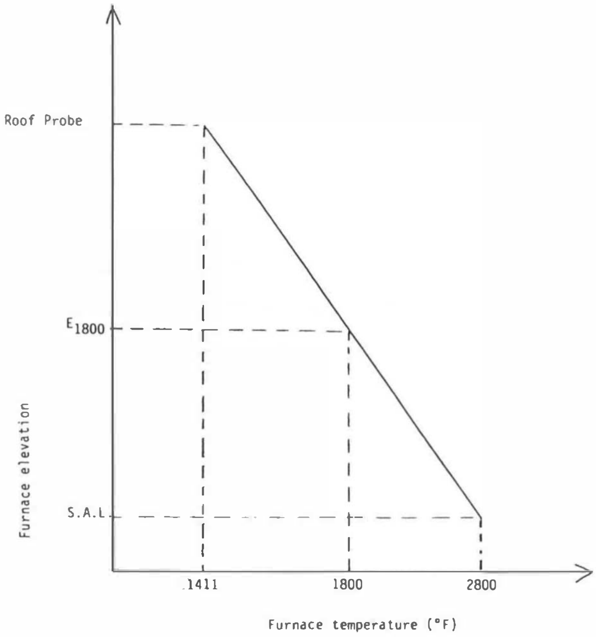


FIG. A FURNACE ELEVATION VS FURNACE TEMPERATURE (°F)