THE DETERMINATION OF THE THERMAL OPERATING CHARACTERISTICS IN THE FURNACE OF A REFUSE-FIRED POWER BOILER

S. A. SCAVUZZO AND J. R. STREMPEK
Fossil Power Division
The Babcock & Wilcox Company
Barberton, Ohio

L. STRACH
Wheelabrator Technologies Inc.
Danvers, Massachusetts

ABSTRACT

Recent concerns over the emission of trace organic compounds from solid waste incineration have led to governmental regulations affecting the design, operation, and maintenance of Refuse-to-Energy facilities. Many state environmental agencies are now implementing time-at-temperature criteria into their operating permits. These criteria vary from state to state but are based on the belief that the destruction of organic compounds is a function of furnace gas residence time-at-temperature in the presence of oxygen in a well-mixed state. Extensive testing is often required to verify permit compliance capabilities and/or to develop correlations for on-line continuous monitoring. This paper discusses the procedure and equipment used to perform time-at-temperature testing at facilities located in Millbury, Massachusetts and Bridgeport, Connecticut and covers typical results of such analyses.

INTRODUCTION

The passage of Section 102 of the Hazardous and Solid Waste Amendments (HSWA) of 1984 was a response to a new level of public concern over the emission of trace organic compounds from municipal waste combustors. This act mandated the Environmental Protection Agency (EPA) to prepare and submit to Congress a report setting forth the combustor design criteria and operating practices deemed appropriate for controlling these emissions [1]. Anticipating this legislation, state permitting agencies began to specify various measurable quantities which, on a design basis, were thought to represent "good combustion practices". Good combustion practices are believed to mitigate emissions of trace organic compounds. Associated with these practices are criteria that include considerations for providing a high combustion gas temperature (1500–1800°F) (816–982°C) for a sufficient length of time (1–3 sec). It was presumed that a combustor designed to these requirements would be capable of operating at high combustion efficiencies.

As a condition of the operating permits for the 1500 TPD (1361 tpd) facility at Millbury, Massachusetts and the 2250 TPD (2041 tpd) facility at Bridgeport, Connecticut it was necessary to demonstrate compliance to these criteria in actual field tests. The field tests were conducted from December 1987 to June 1988.

BACKGROUND

The units tested at Millbury and Bridgeport are two identical balanced-draft Babcock & Wilcox Stirling Power Boilers integrated with Von Roll refuse grate systems (Fig. 1). Each unit utilizes a mass-burn water-

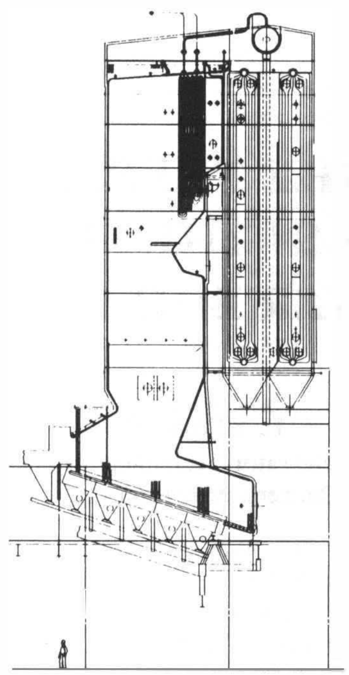


FIG. 1 SIDE VIEW OF A B&W 750 TPD MASS-FIRED POWER BOILER

wall technology designed to process 750 TPD (680 tpd) of Municipal Solid Waste (MSW) and to generate 192,000 lb/hr (87090 kg/h) of superheated steam at conditions of 900 psig (633 kPa) and 830°F (433°C). Each unit is top supported and is arranged with water-cooled furnace walls of gas-tight membrane construction, a three-pass pendant superheater, a modular generating bank, and a modular economizer. The boilers are an integral part of each facility operated by Wheelabrator Technologies Inc. (Fig. 2).

In the combustion process, refuse fuel is converted to heat, gas, and residue by a combination of the "three T's" of combustion: time, temperature, and turbulence [2]. The extent to which combustion may be optimized is a function of the mechanical ability of the combustion system to mix air with fuel. In this case, the combustion system is comprised of the refuse grate system, the air system, the control system, and the furnace [3].

Fuel and air are admitted in a controlled manner by which heat and gaseous products are liberated. As these hot gaseous products pass through the furnace, a portion of their heat is transferred to the surrounding furnace waterwall enclosure. Though control system adjustments can be made to the refuse grate and air systems during operation to optimize combustion conditions, no operational adjustments can be made to the fixed furnace walls. Therefore, the as-built furnace must be capable of successfully handling a wide range of operating conditions [4].

For a given size furnace, the velocity of the gaseous combustion products passing through it is mainly determined by the flow rate of gas present. In turn, the velocity of the gas has a profound effect on:

(a) aerodynamic suspension and transport of particulate matter, and

(b) the time available for the gas to reside in the furnace at a temperature sufficient to complete combustion.

The concept of furnace gas residence time-at-temperature is described by the simultaneous liberation of heat from the combustion of the refuse and the absorption of heat by the furnace waterwalls as the gas moves through the furnace. The combined effects of conduction, convection and radiation heat transfer within the furnace, together with the energy associated with gas mass transfer, can be used to predict the temperature and location of a furnace gas control volume at any given moment in time. When considered over the entire furnace volume, this analysis can be used to generate a thermal operating characteristic, more commonly referred to as a time/temperature curve. This curve provides the design engineer with a basis for evaluating the adequacy of a particular furnace relative to its intended refuse handling capacity [5].

THEORETICAL PREDICTION OF RESIDENCE TIME-AT-TEMPERATURE

The methodology used to predict furnace gas residence time-at-temperature relies upon field-proven methods to determine furnace absorption rates for bare tube and refractory covered enclosure surfaces. Adjustments are incorporated to account for some ash coating. The furnace model is divided into zones to account for the fuel and air introduction locations as well as refractory versus bare tube surface. A computer model is used to calculate temperature, quantity, and composition of gas entering and leaving each zone from the given fuel analysis and excess air. To simplify the model for the complex natural gradients that occur in actual practice, gas temperature and flow are considered to be evenly distributed at each zone boundary. The volumetric gas flow rate for each zone is then determined from gas weight and density at the average temperature of the zone. Finally, the zone residence time is calculated by dividing zone volume by the volumetric gas flow rate.

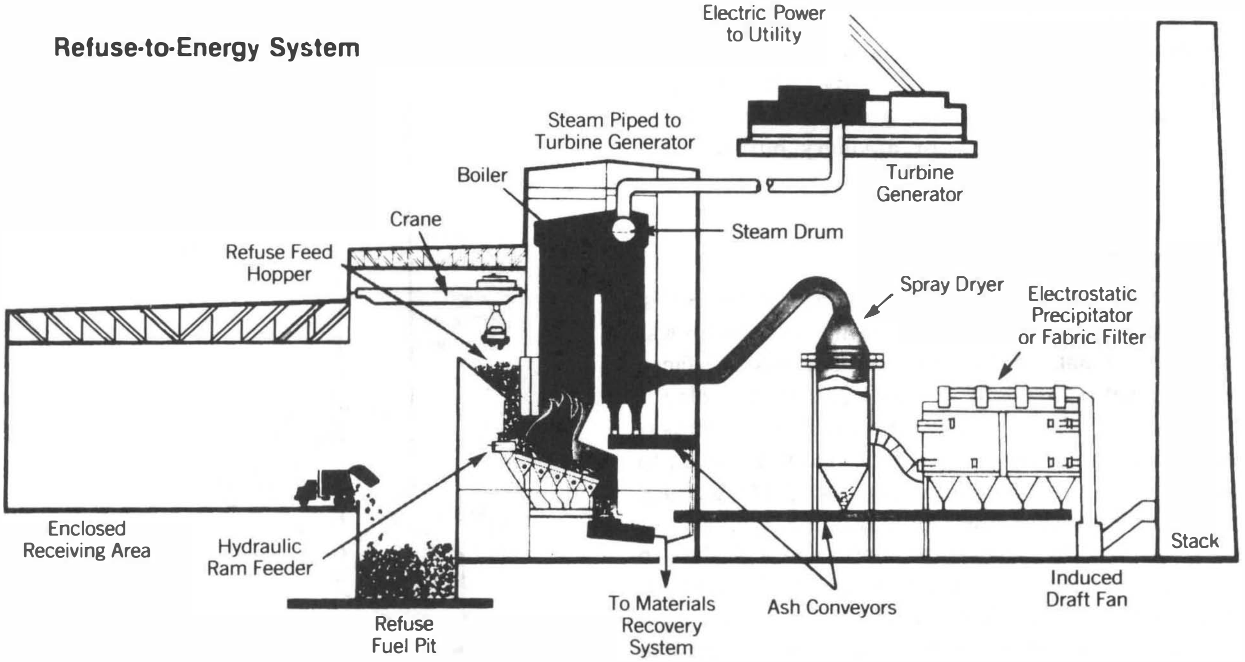


FIG. 2 TEST FACILITY OPERATED BY WHEELABRATOR TECHNOLOGIES INC.

The residence time calculation for each zone in the furnace is as follows:

$$RT_i = \frac{V_i}{G_i} \qquad (1)$$

where: RT_i = residence time in zone i, sec
V_i = volume of zone i, ft^3
G_i = volumetric gas flow rate through zone i, ft^3/sec

$$T_{avg_i} = \frac{(T_{1_i} + T_{2_i})}{2} \qquad (2)$$

where: T_{avg_i} = average temperature in zone i, °F
T_{1_i} = temperature entering zone i, °F
T_{2_i} = temperature leaving zone i, °F

The volumetric gas weight, G_i, can then be determined from:

$$G_i = \frac{Wg_i}{\rho_i * 3600} \qquad (3)$$

where: Wg_i = gas weight entering zone i, lb/hr
ρ_i = gas density at average zone temperature, T_{avg_i}, lb/ft^3
3600 = conversion, sec/hr

By susbstituting, Eq. (1) can be rewritten as:

$$RT_i = \frac{V_i * \rho_i * 3600}{Wg_i} \qquad (4)$$

The cumulative residence time in the furnace (RT) at any point, is the algebraic sum of the residence times of the preceding zones, or:

$$RT = \Sigma_{i=1}^{n} RT_i \qquad (5)$$

where: n is the number of furnace zones.

The time/temperature curve is then derived by plotting the gas temperature and cumulative residence time with the corresponding location of each zone boundary.

FIELD MEASUREMENT OF RESIDENCE TIME-AT-TEMPERATURE

Furnace Conditions

Prior to any testing, the units were commissioned in accordance with the manufacturer's recommendations and run at full load, firing refuse for several weeks to allow the heat absorbing surfaces to attain "commercially clean" conditions. During this time, the automatic combustion controls were tuned and the required plant instrumentation was calibrated.

All tests were conducted at steady state conditions with automatic controls holding a steam flow setpoint. No sootblowers, rappers, or auxiliary burners were operated during the tests.

Test Equipment

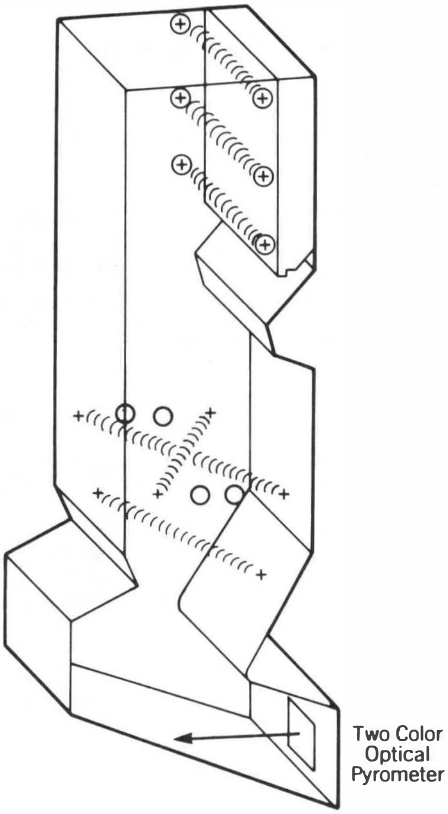
To obtain on-line furnace time/temperature results, an automated data acquisition and analysis system was employed. A data acquisition computer was interfaced with all temporary test instrumentation, the plant's Network 90®[1] data highway, and the furnace temperature measuring system to provide real-time access to all necessary instrumentation. Sensors were scanned on a 15–60 sec time interval, depending on the transient nature of the process, to capture enough data to measure the natural transients that occur in the unit. Multiple scans were then averaged over 10 min time intervals and the data were reduced to develop on-line residence time/temperature curves. The curves were then displayed on the CRT of the data analysis computer. All test data were also archived for future use.

Furnace Temperature Measurement

A necessary parameter for the calculation of furnace residence time-at-temperature is the temperature profile in the combustion zone. It is also one of the most difficult parameters to measure due to the dynamic nature of the combustion process. Historically, water-cooled high velocity thermocouple (HVT) probes have been used to measure gas temperature in high temperature zones. The disadvantages of HVT traverses are that they are manpower-intensive; they take a long time to complete; and they give single-point readings which are often not representative of the conditions during the entire traverse period.

To satisfy the need for instantaneous furnace temperature measurement at multiple locations, a combination of optical pyrometry and acoustic pyrometry was employed.

Acoustic pyrometry is a technique for determining gas temperature based on the propagation speed of acoustic waves [6]. For a given gas composition, the propagation speed varies as the square root of the absolute temperature. The basic objective of this technique is to generate and transmit a unique pattern of acoustic waves, detect their arrival, and accurately measure the transmitter-to-receiver flight time. By knowing the transmission path length and flight time, an acoustic velocity is computed. The specific heat ratio and molecular weight of the flue gas are then used to determine the average temperature along the propagation path.



\+ Denotes pyrosonic transmission path

○ Denotes where HVT were used to verify pyrosonics

FIG. 3 FURNACE TEMPERATURE MEASUREMENT LOCATIONS

Pyrosonic 2000®[2], which employs the acoustic techniques already described, was installed to measure the furnace gas temperature at six locations on five separate elevations. The measurement locations were selected to avoid regions of stratified gas/air which would otherwise have had an adverse affect on the results. HVT traverses were used to verify pyrosonics at all locations prior to testing. A two-color optical pyrometer was used to obtain the temperature just above the grate because test ports for acoustic pyrometry were not available at this location. Figure 3 shows the

---

[1] Network 90 is a registered trademark of The Bailey Controls Co.

[2] Pyrosonic 2000 is a registered trademark of The Babcock & Wilcox Company.

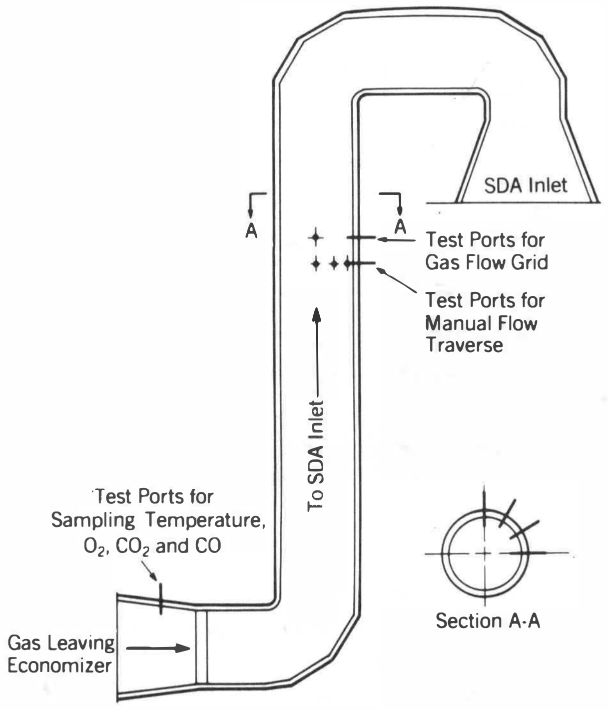


FIG. 4 GAS SAMPLING LOCATIONS AT ECONOMIZER OUTLET

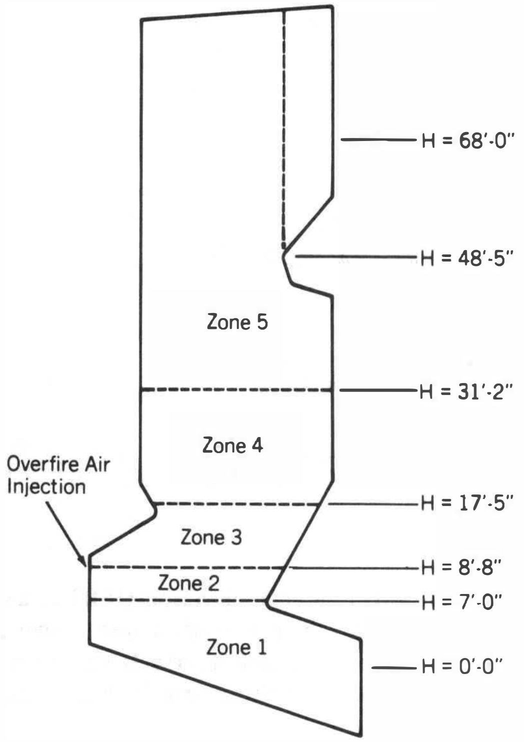


FIG. 5 FURNACE ZONES FOR RESIDENCE TIME CALCULATIONS

location of gas temperature measurements made using the three techniques already described.

Flue Gas Flow Measurement

The actual flue gas flow was measured on-line by a grid of probes designed to measure static and total pressure (Fig. 4). The grid was calibrated by performing manual flow traverses of the flue over the practical load range of the boiler to develop a calibration factor. This factor was used to relate the velocity pressure from the grid to the actual flue gas flow rate. The manual flow traverses were done in general accordance with ASME PTC 11 Fans, using a three-hole, calibrated Fechheimer probe.

Flue Gas Moisture Measurement

Flue gas moisture was obtained in accordance with EPA methods 1, 2, and 4 by traversing the economizer outlet/spray dryer absorber (SDA) inlet flue (reference Fig. 4 for test port locations). The moisture content measured during each test was used for the final calculation of flue gas flow and as a variable input to pyrosonics.

Flue Gas Analysis

A multipoint sampling grid was installed at the economizer gas outlet in general accordance with ASME PTC 19.10. The grid was used to obtain a representative measurement of flue gas temperature and gaseous constituents.

The gas samples were extracted, mixed in composite bubblers, and continuously analyzed for dry volume percentages of O_2, CO_2, and CO. The resulting flue gas analysis was used as a variable input to pyrosonics; to calculate gas density; and to calculate the gas weight below the elevation of overfire air (OFA) injection. Figure 4 denotes the locations of the sampling grids used to determine gas constituents.

DETERMINATION OF RESIDENCE TIME/ TEMPERATURE CURVES

The furnace was divided into zones as defined by location of temperature measurement devices and the location of OFA injection, as shown in Fig. 5. The gas temperatures at the upper boundaries of zones 1 and 2 were interpolated from temperatures measured at the zero reference elevation and the upper boundary of

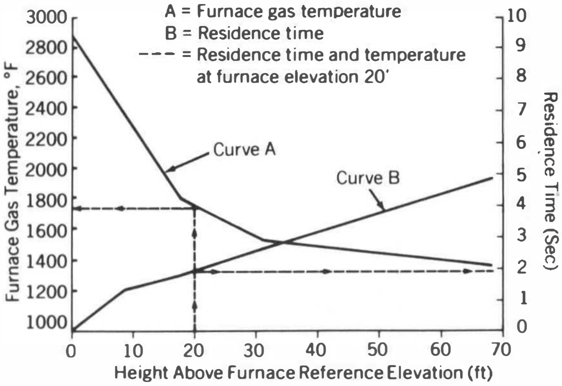


FIG. 6 GAS TEMPERATURE AND RESIDENCE TIME VS FURNACE HEIGHT AT FULL LOAD

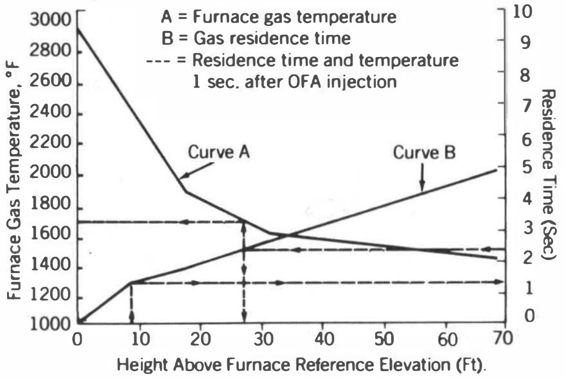


FIG. 7 GAS TEMPERATURE AND RESIDENCE TIME 1 sec AFTER OFA INJECTION

zone 3. The zero reference elevation (0 ft) is defined as the elevation at which a vertical line drawn from the tip of the front wall arch intersects the grate. The reference elevation is arbitrary and has no effect on the results.

Because approximately 45% of the combustion air enters the furnace through the OFA ports, it is necessary to account for the lower gas weight below this elevation. The furnace gas weight, below OFA injection, was approximated by subtracting OFA from the measured gas weight at the boiler exit. The measured undergrate to overfire air ratio was obtained from the plant's permanent instrumentation.

The gas density was calculated using gas analysis from the economizer outlet and the average measured temperature in each of the furnace zones. The gas residence time in each zone was then determined using Eq. (4).

PRESENTATION AND INTERPRETATION OF RESULTS

Steady state tests, of 4 hr duration, were conducted at several boiler steam loads representing the practical operating range of the units. The data recorded during each of the test runs was averaged and reduced to develop time-at-temperature relationships. Test results obtained from both of the units were in close agreement.

Figure 6, produced from full-load test data recorded at the Bridgeport facility, is a graphical representation of the algorithm used to interpolate the gas temperature and cumulative residence time at any given elevation in the furnace. As an example, Fig. 6 can be used to interpolate the residence time to be 1.9 sec at an elevation of 20 ft (6.1 m). The corresponding gas temperature of 1775°F (968°C) may then be read from the temperature ordinate.

The residence time and associated gas temperatures between any two elevations may also be determined with time/temperature curves. Figure 7 is identical to Fig. 6 except that tutorial lines have been added to show how to interpolate the gas temperature one second after OFA injection. Beginning on the abscissa at 8.7 ft (2.65 m), follow a vertical path to the intersection of the residence time curve B. The value read from the residence time ordinate, 1.3 sec, is the residence time at the elevation of OFA injection. Add 1 sec to determine the time at 1 sec after OFA injection, 2.3 sec. Following a horizontal path back to the residence time curve B, the elevation at 1 sec after OFA injection is determined, 27 ft (8.2 m). A vertical path is then followed until it intersects with the gas temperature curve A and the gas temperature one second after OFA injection may be read from the gas temperature ordinate.

The test data show that the elevation of a given temperature plane within the furnace changes as boiler load and other factors change. Similarly, the gas temperature at a given residence time downstream of a reference point changes as boiler load and other factors change. To illustrate this point, reference Fig. 7 to find the elevation of the plane where gas residence time is 1 sec after OFA injection, 27 ft (8.2 m). Figure 8 is a plot of gas temperature and residence time at elevation 27 ft (8.2 m) versus steam flow. Note that as unit load decreases, gas temperature at elevation 27 ft (8.2 m) decreases as expected, and residence time at 27 ft (8.2 m) increases substantially. This example clearly demonstrates that it is not possible to install a

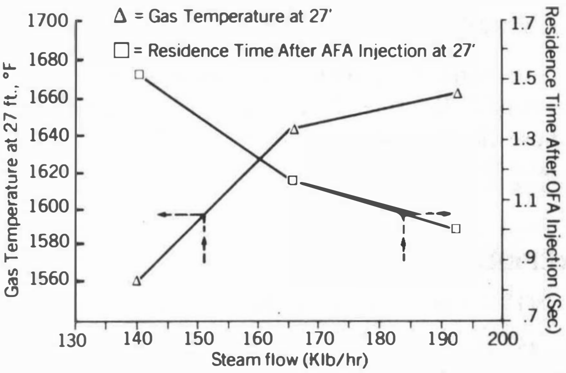


FIG. 8 RESIDENCE TIME AFTER OFA AT 27 ft AND GAS TEMPERATURE VS STEAM FLOW

temperature monitor on the furnace wall at a position representing one second of residence time after OFA injection for all possible operating conditions.

Figure 9 is a comparison of the gas temperature at one second residence time after OFA injection for two different load points. It is identical to Figs. 6 and 7 except that the time/temperature curves developed from the low steam load test at 140,000 lb/hr (63,500 kg/h) have been included. Although it seems logical that the gas temperature at a given residence time should decrease with load, Fig. 9 shows that the gas temperature at 1 sec after OFA injection is actually higher at the low load condition than at the high load condition. This occurs because at low load, the reduced gas weight has more of an effect on residence time-at-temperature than does the generally lower gas temperatures. This further illustrates the dependence of residence time-at-temperature on unit operating conditions.

In order to evaluate the influence of varying operating conditions on residence time-at-temperature, a second test was conducted at the full load condition presented in Figs. 6, 7, and 9. This test was conducted several days later to allow for potential changes in fuel and furnace conditions; additionally, the unit was operated with approximately 25% lower excess air. Figure 10 is a plot of the time/temperature curves developed from the two full load tests which shows that both gas temperature and residence time were affected by changes in operating conditions.

Based on the analysis of the Millbury and Bridgeport test data, the following is noted:

(a) The thermal operating characteristics of a refuse-fired power boiler can be monitored on-line.

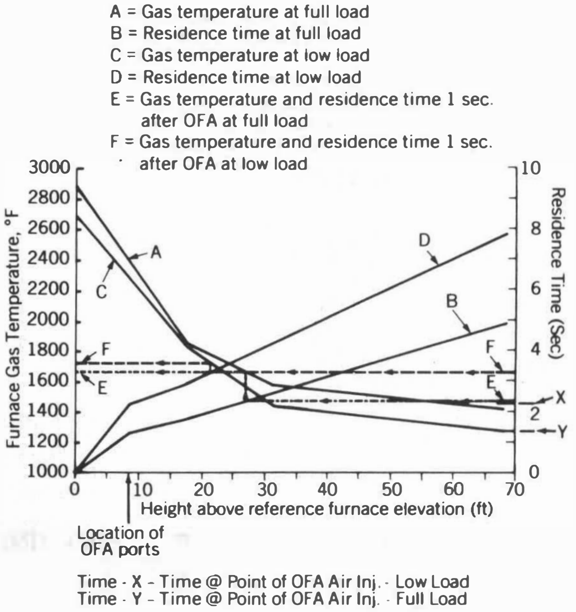


FIG. 9 GAS TEMPERATURE AT 1 sec RESIDENCE TIME AFTER OFA INJECTION VS FURNACE HEIGHT

(b) Acoustic pyrometry is an effective means of measuring instantaneous temperatures at multiple locations in the combustion zone.

(c) Both of the units tested satisfied the permit requirements for residence time-at-temperature.

(d) There is not a single location in the furnace representative of one second residence time for all operating conditions.

(e) Residence time-at-temperature is affected by a number of variables including unit load and excess air.

The test results were submitted to the respective State authorities and final operating permits were subsequently granted.

Furnace temperatures and residence times are continuously monitored utilizing permanent thermocouples (located behind the superheater) and graphs developed from this test program.

SUMMARY

The dynamic nature of flow and temperature conditions in the furnace of a refuse-fired power boiler requires rigorous measurement and analytical techniques. The application of fundamental heat transfer and gas dynamics principles, together with state-of-the-art measurement and data acquisition, provides the technology to determine the actual thermal operating

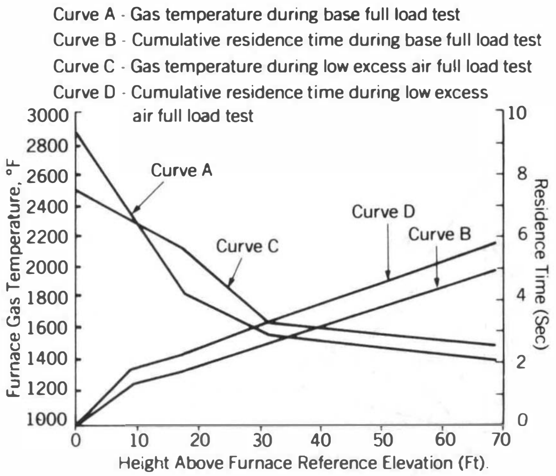


FIG. 10 GAS TEMPERATURE AND RESIDENCE TIME AT TWO FULL LOAD CONDITIONS

characteristics. This technology has been successfully used to demonstrate compliance with furnace gas residence time-at-temperature requirements at two commercial Refuse-to-Energy facilities. The test results confirm the theoretical basis used in the prediction of residence time-at-temperature, and will enable subsequent predictions to be made with greater confidence.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of J. D. Blue, T. C. Heil and R. E. Smolenski, whose efforts made this paper possible.

REFERENCES

[1] Greene, S. "Municipal Waste Combustion Study: Report to Congress." EPA/530-SW-87-021A, June, 1987, vi.

[2] The Babcock & Wilcox Company. "Principles of Combustion." In *STEAM/Its Generation and Use.* Thirty-nineth edition. New York, 1978, 6-1.

[3] Elliott, T. C. (ed.). "Waste Fuels: Their Preparation, Handling, and Firing." In *Standard Handbook of Powerplant Engineering.* New York: McGraw-Hill. Inc. 1989. 3.126–3.136.

[4] Blue, J. D., and Strempek, J. R. "Consideration for the Design of Refuse-fired Water Wall Incinerators." Presented to Energy from Wastes Conference Opportunities in an Emerging Market, Power Magazine, SynFuels Waste to Energy Report, Washington D.C., October 24–25, 1985.

[5] Gibbs, D. R., Blue, J. D., and Hepp, M. P. "Design and Operating Experience With High Temperature and High Pressure Refuse-fired Power Boilers." In *Proceedings of the 1988 National Waste Processing Conference,* Philadelphia, Pennsylvania, May 1-4, 1988. New York: The American Society of Mechanical Engineers.

[6] Larsen, P. S. "Continuously Monitoring Furnace Temperatures in Refuse Boilers Using Acoustic Pyrometry." "*Proceedings of the 1986 National Waste Technology Conference,* Chicago", Illinois, October 20–22, 1986. New York: The American Society of Mechanical Engineers.

Key Words: Combustion; Emissions; Operation; Organic(s); Temperature