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FLUIDIZED-BED WASTE-HEAT RECOVERY SYSTEM DEVELOPMENT

Semiannual Report for February 1—July 31, 1982

By
William E. Cole
Robert DeSaro
James Griffith
Chandrashekhar Joshi

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ABSTRACT

A major energy loss in industry is the heat content of the flue gases from industrial process heaters. One effective way to utilize this energy, which is applicable to all processes, is to preheat the combustion air from the process heater. Although recuperators are available to preheat this air when the flue gases are clean, recuperators to recover the heat from dirty and corrosive flue gases do not exist.

The Fluidized Bed Waste Heat Recovery (FBWHR) System is designed to preheat this combustion air using the heat available in dirty flue gas streams. In this system, a recirculating medium is heated by the flue gas in a fluidized bed. The hot medium is then removed from the bed and placed in a second fluidized bed where it is fluidized by the combustion air. Through this process, the combustion air is heated. The cooled medium is then returned to the first bed. Initial development of this concept is for the aluminum smelting industry.

In this report, the accomplishments of the succeeding six-month period are described.

EXECUTIVE SUMMARY

A major energy loss in industry is the heat content of flue gases from industrial process heaters. One effective way to utilize this energy, which is applicable to all processes, is to preheat the combustion air from the process heater. Although recuperators are available to preheat this air when the flue gases are clean, recuperators to recover the heat from dirty and corrosive flue gases do not exist. Hence, much of this heat is lost with the flue gases.

The Fluidized Bed Waste Heat Recovery (FBWHR) System is designed to preheat this combustion air using the heat available in dirty flue gas streams. In this system, a recirculating medium is heated by the flue gas in a fluidized bed. The hot medium is then removed from the bed and placed in a second fluidized bed where it is fluidized by the combustion air. Through this process, the combustion air is heated. The cooled medium is then returned to the first bed. Initial development of this concept is for the aluminum smelting industry.

Previous accomplishments in this development, described in Report No. DOE/ID/12302-1 include:

- Development of the Medium Feed System to Transfer Medium from the Hot to the Cold Bed;
- Analytical Development and Experimental Verification of the Distributor Plate Stability Criteria (the distributor plate is required to stabilize the fluidized bed);
- Investigation of Alternative Distributor Plate Configurations and Materials; and,
- Assembly of a Microcomputer-Based Data Acquisition System to Monitor Baseline Furnace Performance.

In this report, the accomplishments of the succeeding six-month period are described. Specific accomplishments include:

- Completion of the FBWHR System Conceptual Design;
- Characterization of the Host-Site Furnace Operations;
- Continued Materials Coupon Tests;
- Distributor Plate Fouling Tests;
- Specification for Most Major Hardware; and,
- Definition of the FBWHR System Control Methodology.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

1. INTRODUCTION

A major energy loss in industry is caused by heat loss through stack gases from industrial process furnaces. In many industries, stack gases from high-temperature process heaters are discharged directly to the atmosphere at high temperatures, wasting a significant fraction of the thermal energy input. In many cases, the stack gas temperature is 2000°F or higher, corresponding to a flue gas loss of 55 percent or greater. The energy loss in the flue gas in any direct heating process is shown in Figure 1.1 as a function of the flue gas temperature. In 1977, direct heating processes in the U.S. industrial sector used about 11 percent of the national energy consumption of all types, or about 8.4×10^{15} Btu/hr,* and the major fraction of this energy was provided by combustion of natural gas and fuel oil. If an average saving of 15 percent were achieved by widespread application of heat recovery systems to industrial process furnaces, national yearly savings in premium fuel consumption would be 1.26×10^{15} Btu/yr, sufficient to heat about 18 million homes every year.

The most universally applicable use of the energy content of the flue gas is for preheat of the combustion air by a heat recovery regenerator/recuperator as illustrated in Figure 1.2. The heat recovered results in a greater than one-to-one reduction in the fuel input to the furnace for a given heating duty; 1 Btu recovered results in more than 1 Btu reduction in the fuel input. The percent savings in fuel consumption by use of the heat recovery unit is presented in Figure 1.3 as a function of the furnace exit exhaust gas temperature and the heat transfer effectiveness of the regenerator/recuperator. The percent energy savings by use of a 60-percent effective regenerator ranges from 13 percent at a furnace exit temperature of 1000°F to 48 percent at a furnace exit temperature of 2400°F.

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*Gerstner, M., and Stake, R., "Survey of Potential Energy Savings Using High Effectiveness Recuperators for Waste Heat Recovery from Industrial Flue Gases," TID-28954, prepared for U.S. Department of Energy by AiResearch Manufacturing Company, Torrance, California, October 15, 1977.

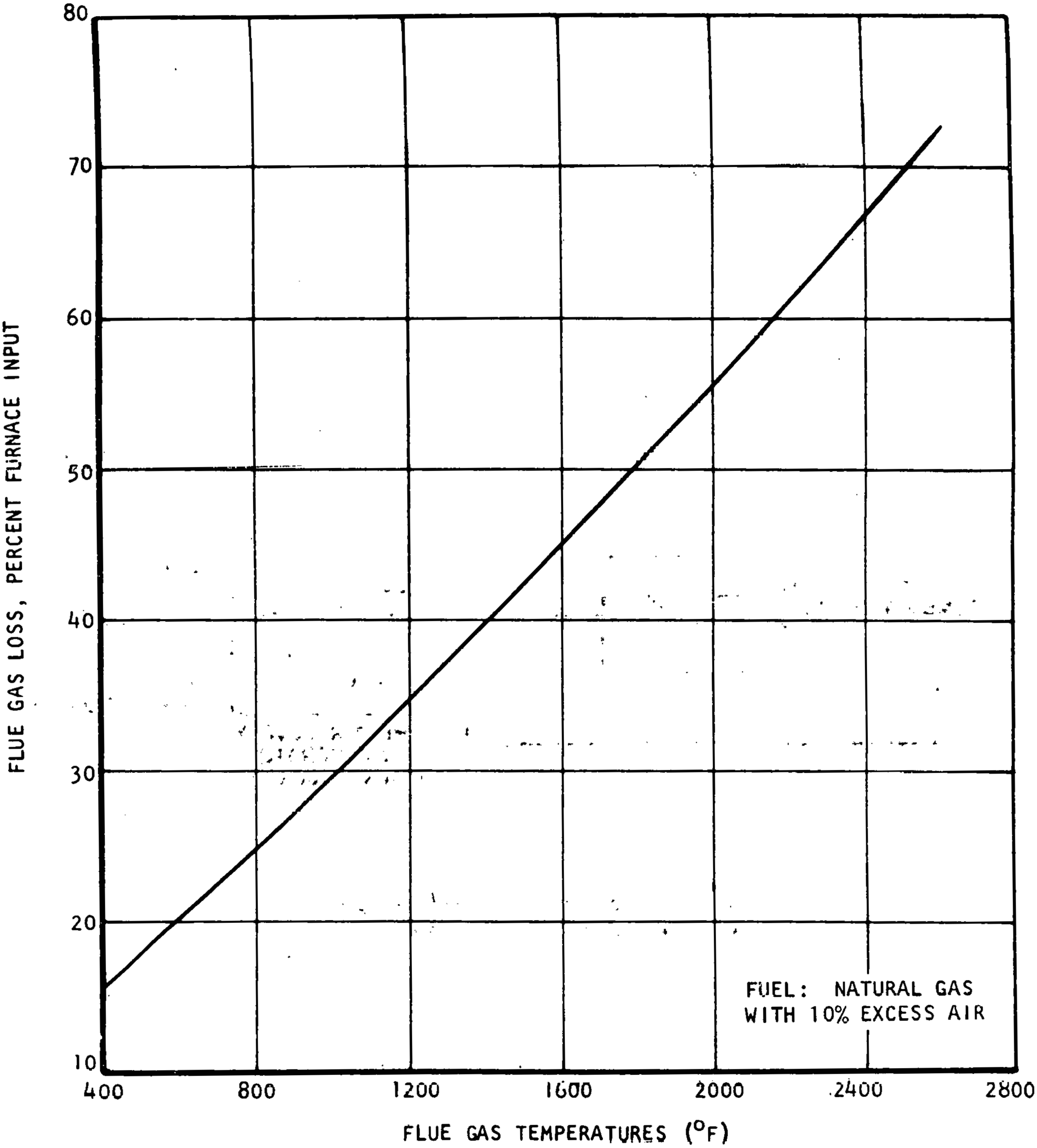

Figure 1.1 Energy Loss in Flue Gas in Any Direct Heating Process

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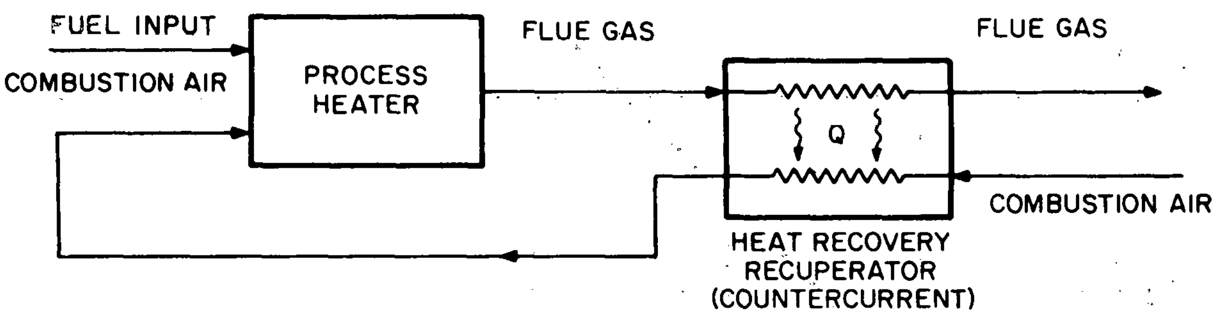

Figure 1.2 Schematic of Regenerator/Recuperator Heat Recovery for Industrial Process Heater

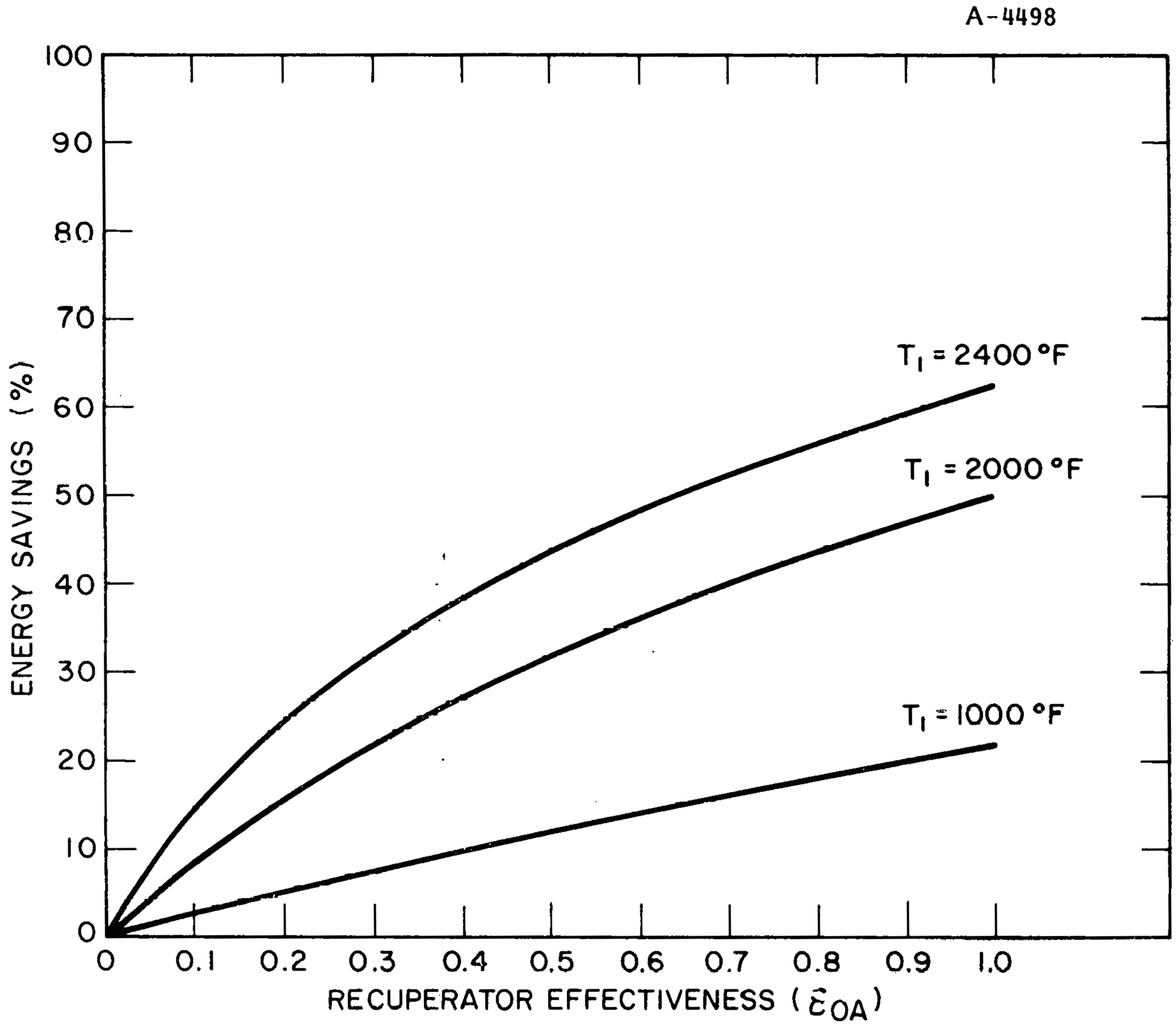

Figure 1.3 Percent Savings in Fuel Consumption as Function of ε_{OA} with Furnace Exit Temperature, T_1, as Parameter (Natural Gas, 10% Excess Air)

The savings would be even greater for a higher effectiveness recuperator.

However, universally applicable recuperators for recovery of this waste heat are not available because most of these gas streams are at high temperatures and contain dirty or corrosive contaminants. These severe environments create materials problems for existing recuperator designs. Thus, the key to developing a universally applicable recuperator is serviceability in this environment. The second most important criterion is that the unit be low in cost which is necessary to ensure that the heat exchanger can be amortized over a reasonable period of time and, hence, will be widely purchased by energy users. These two criteria are more important than high effectiveness. To demonstrate this, consider, for example, a furnace with 2000°F exhaust gases. A moderate effectiveness recuperator (50 percent) will save a little over 30 percent of the energy input. A high effectiveness recuperator (90 percent) will increase this energy savings to 45 percent – a 50-percent increase. Hence, two-thirds of the benefit was purchased for only a fraction of the recuperator heat transfer area. Looking at specific firing rates, a moderate effectiveness recuperator reduces the firing rate to 680,000 Btu/hr per MMBtu/hr on the unrecuperated furnace, and a high effectiveness recuperator reduces the firing rate to 550,000 Btu/hr per MMBtu/hr on the unrecuperated furnace. Hence, the need is to get heat recovery equipment installed on the furnace and then strive to increase its effectiveness.

The objective of this program is to develop a fluidized-bed waste-heat recovery (FBWHR) system to preheat the combustion air, while meeting these criteria. This system will have very wide applicability and thus it has the greatest potential for maximum energy savings through recovery of currently wasted heat. Of particular importance is the ability of the fluidized-bed unit to operate with dirty and corrosive flue gases, a major impediment to industrial heat recovery in the past. The proposed unit will also have high reliability, an adequate service life, and be low in cost resulting in a short amortization period.

Figure 1.4 is a drawing of the FBWHR system. The system consists of two fluidized beds, one mounted above the other. The exhaust gases from the furnace at 2000°F pass through the upper fluidized bed and heat the particles. These heated particles are then transferred to the lower bed where they are used to preheat the incoming combustion air. The cooled particles are then returned to the upper bed for reheating.

Initial demonstration of this system will be for the aluminum smelting industry. Aluminum smelting is the process of melting scrap aluminum, alloying it into a specified alloy, and casting it into a finished product. There are currently 91 secondary aluminum plants in the United States.* Output from these plants was 1,371,000 tons in 1976. This was 27 percent of domestic aluminum consumption of 5,118,000 tons.** There are two sources of aluminum scrap material, new scrap and old scrap. New scrap is waste material created in the manufacturing process; it is directly related to production, and over 90 percent is recycled. Old scrap is that material fabricated into finished products and discarded by the ultimate purchaser. Only a small fraction of old scrap is recycled, and over 2 million tons are lost yearly to municipal and commercial waste.

The problem with using standard metallic recuperators on aluminum smelting furnaces is the very corrosive flue gases. The primary contaminant in scrap aluminum is magnesium. To remove the magnesium, chlorine is bubbled through the melt, forming magnesium chloride, which is easily skimmed off. Unfortunately, some of the chloride escapes into the flue gases and up the stack resulting in a severe corrosion problem with standard metallic recuperators. Thus, no satisfactory recuperator is available to recover the waste heat from the over 2000°F flue gases produced by these furnaces. Hence the development of the FBWHR system.

Vulcan Material Company (VMC) will host the demonstration of the FBWHR system. VMC is the country's third largest secondary producer

*Aluminum Statistical Review, The Aluminum Association, 1976.
**Starper, J.W. and Kurtz, H.F., Mineral Facts and Problems, Bureau of Mines Bulletin No. 667 (1975).

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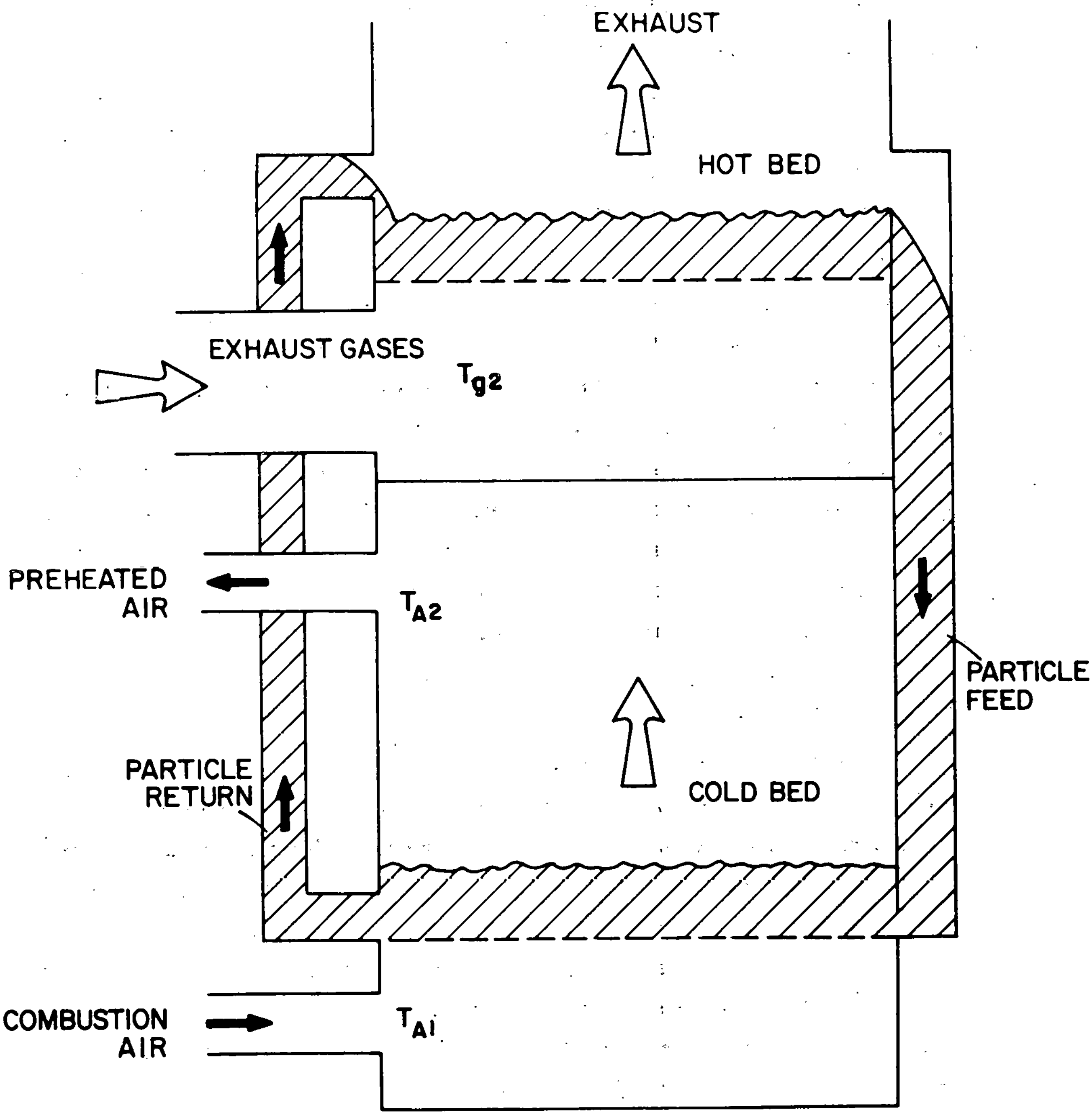

Figure 1.4 Fluidized-Bed Air Preheat System

of aluminum, tin, zinc, and lead. Their aluminum operations are the subject of the demonstration program. VMC has 25 aluminum furnaces, all similar, located in four plants throughout the country.

Furnace No. 2, shown schematically in Figure 1.5, will be used in this demonstration program. The left side of this schematic shows where the aluminum is loaded into the furnace. This charge floats on a pool of liquid aluminum and is gradually melted over a 12-hour period. The furnace uses three burners for a total rating of 24 MMBtu/hr. After melting, the aluminum is alloyed, and any unwanted contaminants are removed over a 6-hour period. The aluminum is then drawn off and cast into either 30-lb ingots or 1000-lb sows, or prepared in molten form for shipment in insulated ladles to the customer's plant.

Figure 1.6 shows the FBWHR system integrated with VMC's No. 2 furnace. The exhaust gases enter the upper fluidized bed prior to exhausting to the atmosphere. Preheated combustion air, from the lower bed, enters the burners.

During this reporting period, work proceeded on the design of the FBWHR system and upon characterizing furnace operations. Specifically:

- The FBWHR system conceptual design was completed;
- The host-site furnace operations were characterized;
- Specifications of most major hardware were completed;
- Fouling and materials tests were continued; and
- The FBWHR system control methodology was defined.

Details of these accomplishments are presented in this report.

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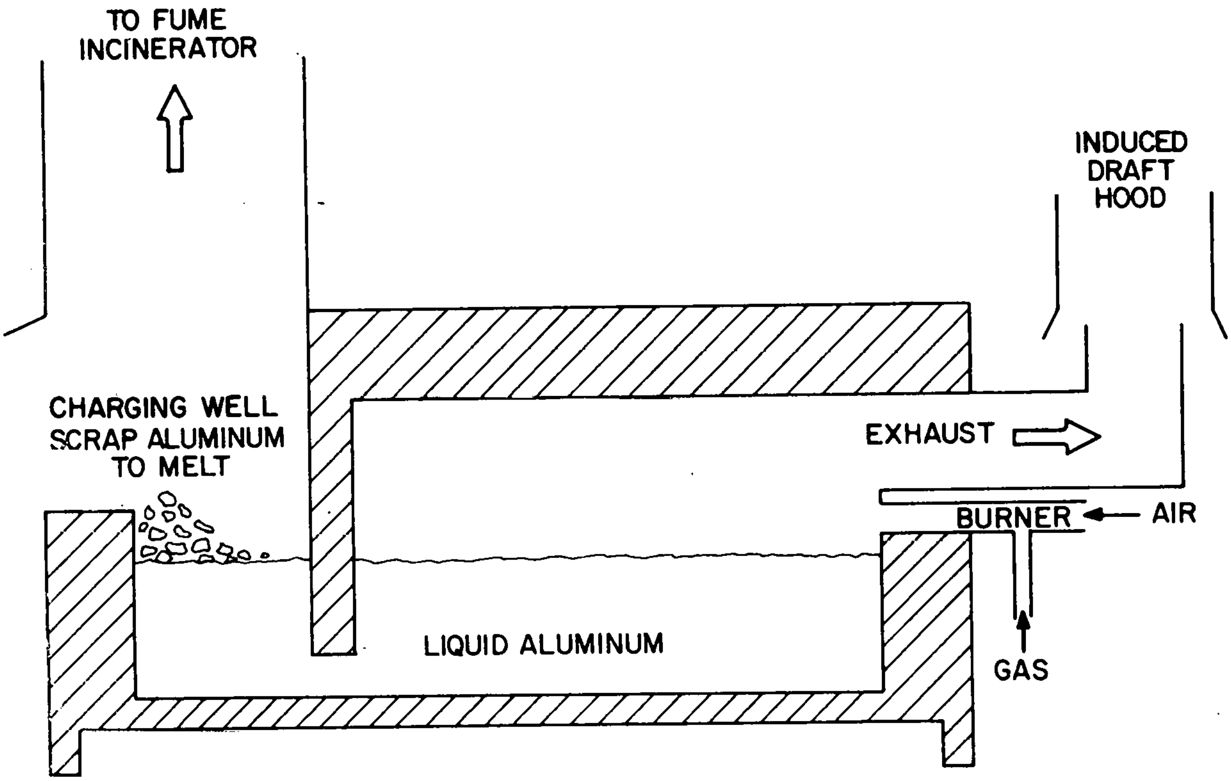

Figure 1.5 Aluminum Smelting Furnace

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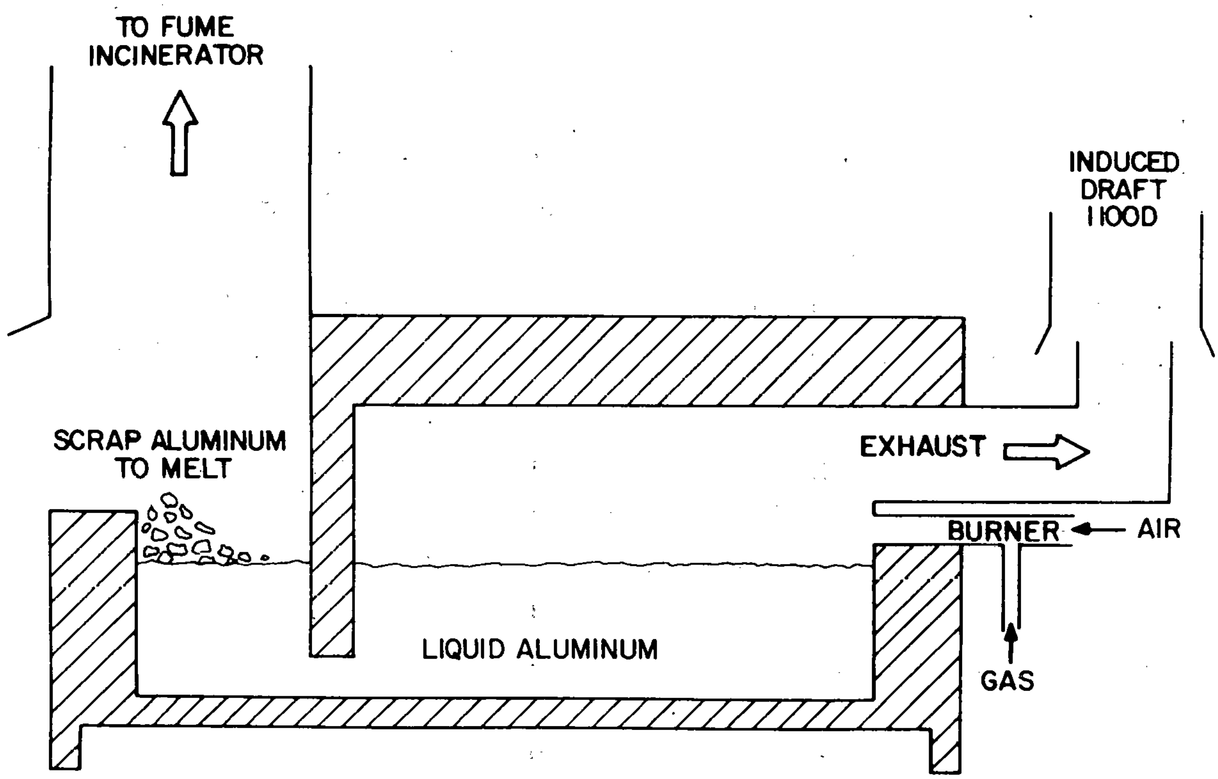

Figure 2.1 Aluminum Smelting Furnace

2. HOST SITE CHARACTERIZATION

2.1 INTRODUCTION

Vulcan Materials Co. (VMC) is the host company for the FBWHR system development. VMC is a major smelter of secondary aluminum and the tests will be performed in their Sandusky plant. At the VMC Sandusky Operations, the aluminum scrap material is received by either truck or rail. Much of this material is crushed to a uniform size, and any paint, oil, or dirt is removed in a rotary drier. The aluminum scrap is then smelted in a batch process using an open hearth reverberatory furnace. Figure 2.1 is a schematic of the furnace which shows where the aluminum is loaded into the furnace. The charge floats on a pool of liquid aluminum and is gradually melted. Melting this charge takes 12 hours. During melting, the aluminum is alloyed, and any unwanted contaminants are removed. The aluminum is then drawn off and cast into 30-lb ingots, 1000-lb sows, or shipped in molten form in insulated ladles to the customer's plants.

Heat for melting the aluminum is provided by burning natural gas. Unpreheated air is provided to the burners by a blower, at a maximum pressure of 8 oz/in.^{2}. Three burners fire over the melt, each with a capacity of 8 MMBtu/hr for a maximum firing rate of 24 MMBtu/hr. The flue gases are exhausted from the furnace into an induced draft hood at the same end of the furnace as the burners. Exhaust temperatures range from 1400°F to 2200°F over the production cycle.

Burner firing rate is controlled using two thermocouples; one measuring the flue gas temperature and one the melt temperature. The desired temperature is set by the operator. During the charging cycle, the flue gas temperature is set at 2100°F and the melt temperature at 1400°F. During standby both settings are reduced. If both of the thermocouples call for heat, the burners will fire at a rate proportional to the difference between the set and measured melt temperature. If this difference exceeds 30°F, the burners will fire at maximum capacity. The flue gas thermocouple provides over-temperature protection. If the measured flue gas

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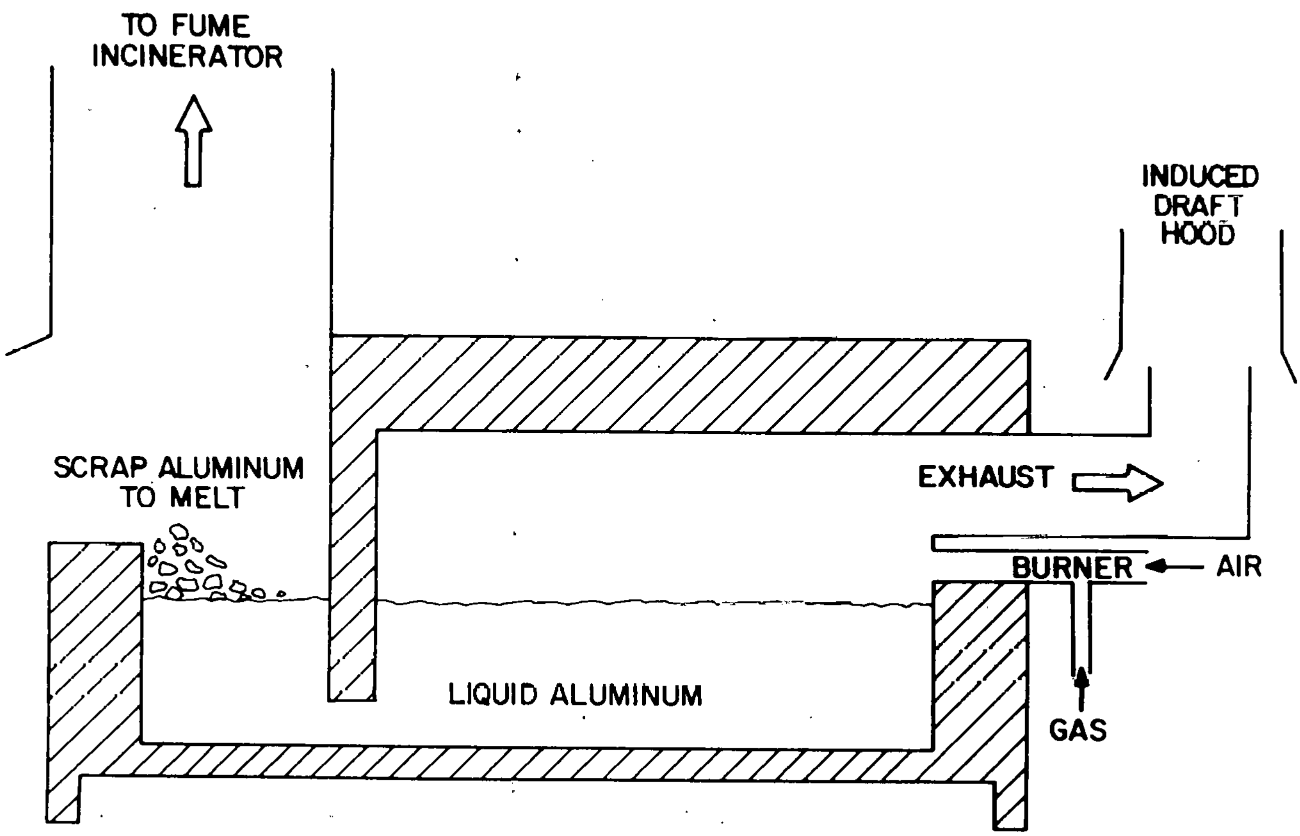

Figure 2.1 Aluminum Remelting Furnace

temperature exceeds the set temperature, the burners are turned off. The operator is free to change the settings and, hence, the firing rate at any time. It is not uncommon for the operator to shut down the burners during the charging cycle.

The furnace pressure is maintained by an air jet damper located at the exit of the flue. Flue pressures are 0.12 in. wc during charging and 0.04 in. wc during standby operations. The 0.12 in. wc value is higher than desired by VMC but the damper is incapable of reducing it further. This may be due to an undersized flue.

During the charging cycle, chlorine is injected into the open hearth to remove unwanted magnesium. The chlorine combines with the magnesium to form magnesium chloride which floats to the top of the melt and is skimmed off. The chlorinating system is new and is still in the development stage. In addition, potash is manually added to the melt to combine with trace metal impurities which are also skimmed off. The combination of chlorine and potash compounds can, at times, enter the furnace and exhaust out the flue. The FBWHR system components that are exposed to the flue gas must withstand these compounds.

In order to match the recuperator to VMC's host furnace, operational data such as air and fuel flow rates, flue gas temperature, and furnace turndown are required. For instance, the upper distributor plate can be sized only after the flue gas flow rate is known. Further, to document the effect of the recuperator, it is necessary to record the furnace performance before and after the recuperator is installed. Unfortunately, the data needed for the design and baseline are not normally recorded by VMC. For that reason, a characterization of VMC's host furnace was undertaken. The characterization was conducted by the following methods:

1. On-site inspections,

2. On-site small-scale experiments in the host furnace flue, and

3. Continuous data acquisition of the host furnace.

The following sections document the results of the furnace characterization.

2.2 FURNACE DATA ACQUISITION

An automatic data acquisition system was assembled to monitor the furnace operations. A photograph of the unit is shown in Figure 2.2. The system uses a Hewlett-Packard Model 85A microcomputer and a Model 3497A data acquisition module. The capabilities of this system include monitoring 40 channels of analog and 16 channels of digital data. The system was installed in Sandusky to monitor furnace No. 2 operations. Specifically, air and fuel flow rates to each burner, flue gas temperature, and aluminum temperature are being monitoring continuously. These data are recorded on a magnetic tape for later analysis. Channel sampling frequency can be varied for each channel, limited only by tape capacity and the computer clock.

2.2.1 Furnace Operations

An overview of the furnace operations is shown in Figure 2.3. The burner air flow rate is plotted over a typical two-week period. The operation of the furnace is cyclic with wide variations in operating parameters. The flow rate varies from over 15,000 lb/hr during high fire to zero during low fire. (A probable zero shift in the instrumentation accounts for the finite reading at low fire in this figure.) Further, the flow rate often changes abruptly from high to low fire indicating the burners are operating in an on-off mode. This type of cyclic on-off operation can occur for a week or more.

Smelting is sometimes suspended during the weekend. At about 72 hours, on Figure 2.3, a weekend is encountered. The burner flow rates are reduced and the burners fire only long enough to keep the remaining melted scrap at about 1300°F. Also, the firing rate is considerably reduced below that needed during charging.

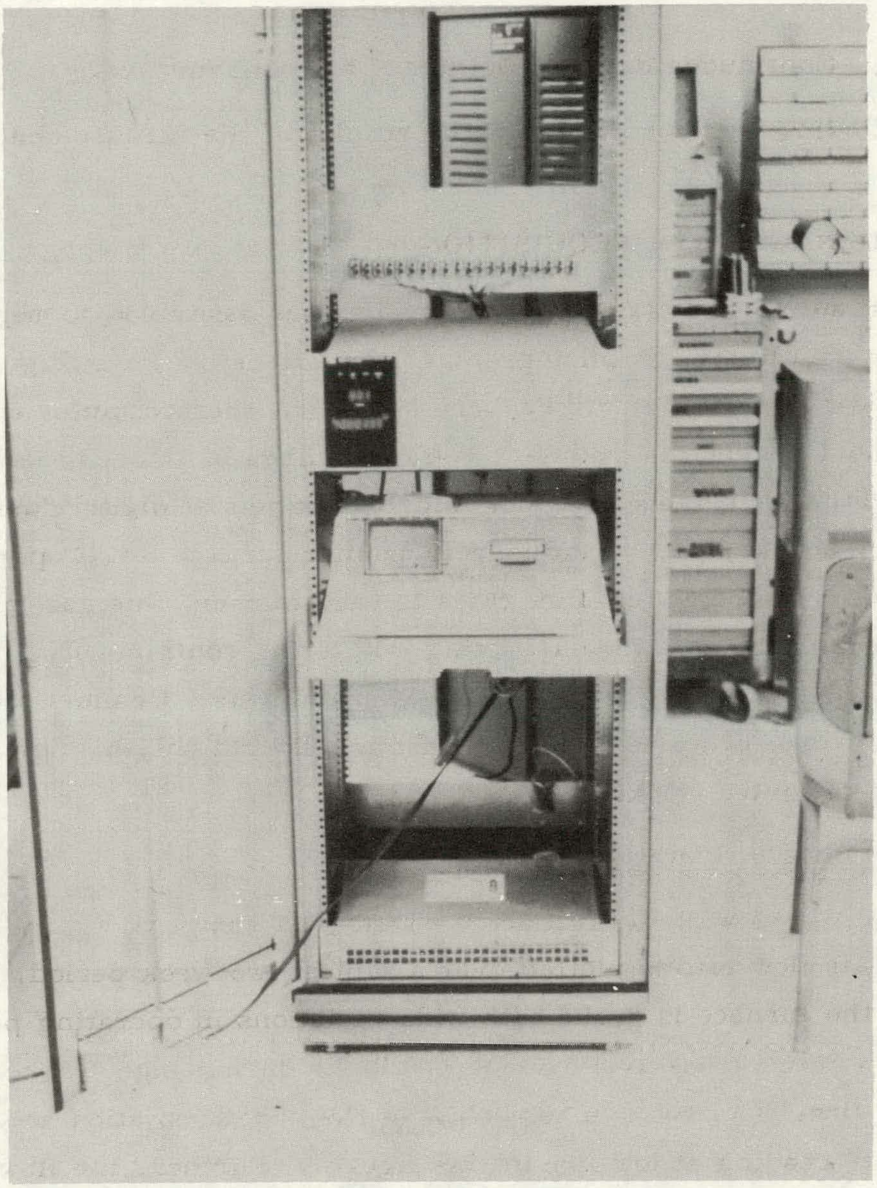

Figure 2.2 The Automatic Data Acquisition Unit

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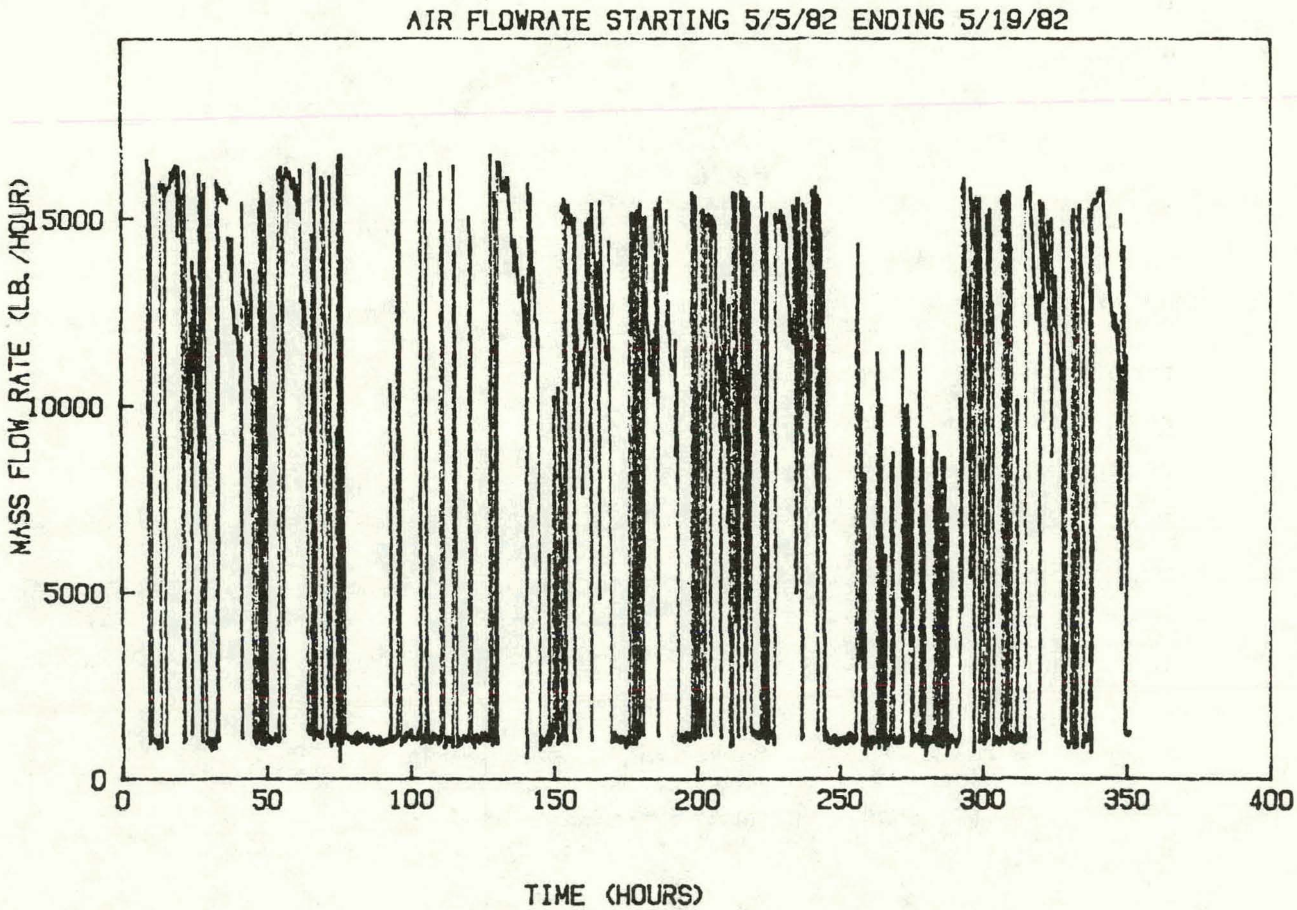

Figure 2.3 Total Burner Air Flow for a Typical Two Week Period

The flue gas temperature corresponding to the air flow rate of Figure 2.3 is shown in Figure 2.4. The maximum flue gas temperature during charging is about 2200°F. During the weekend suspension period, the maximum flue gas temperature is 1350°F.

2.2.2 Furnace Flow Rate

Actual furnace operations are shown in Figure 2.5, an analogous plot to Figure 2.4. For the first 10 hours no scrap is being charged, and the burners are mostly firing at a reduced rate. During scrap charging (10 hours and beyond on Figure 2.5) the burners fire almost continuously at high fire. Generally, the burner flow rate is constant during this period. The decline shown between 10 and 20 hours in Figure 2.5 is typical of the completion of a charging cycle. As the scrap remaining in the furnace is melted, the melt temperature rises. Since the flow rate is proportionately controlled by the melt temperature, the flow rate declines.

Occasionally, a spiked decrease in the flow rate is encountered. This is usually due to manual override by the operator. For instance, it is necessary to periodically stir the melt in the furnace. To do this, the burners must be manually turned off.

The fuel flow rate corresponding to Figure 2.5 is shown in Figure 2.6. Changes in the fuel flow rate and air flow rate are coupled, typical of ratio control. Percent changes in the fuel flow rate are almost identical with percent changes in the air flow rate resulting in a more or less fixed air/fuel ratio as shown in Figure 2.7. An air/fuel ratio of 20 (by mass) corresponds to about 16 percent excess air.

The total flue gas flow rate is the sum of the combustion air flow rate, fuel flow rate, and furnace leakage. Neglecting leakage, the flue gas flow rate, based on the preceding plots, is about 4.8 lbm/sec during charging. The preceding data were gathered from burners that had

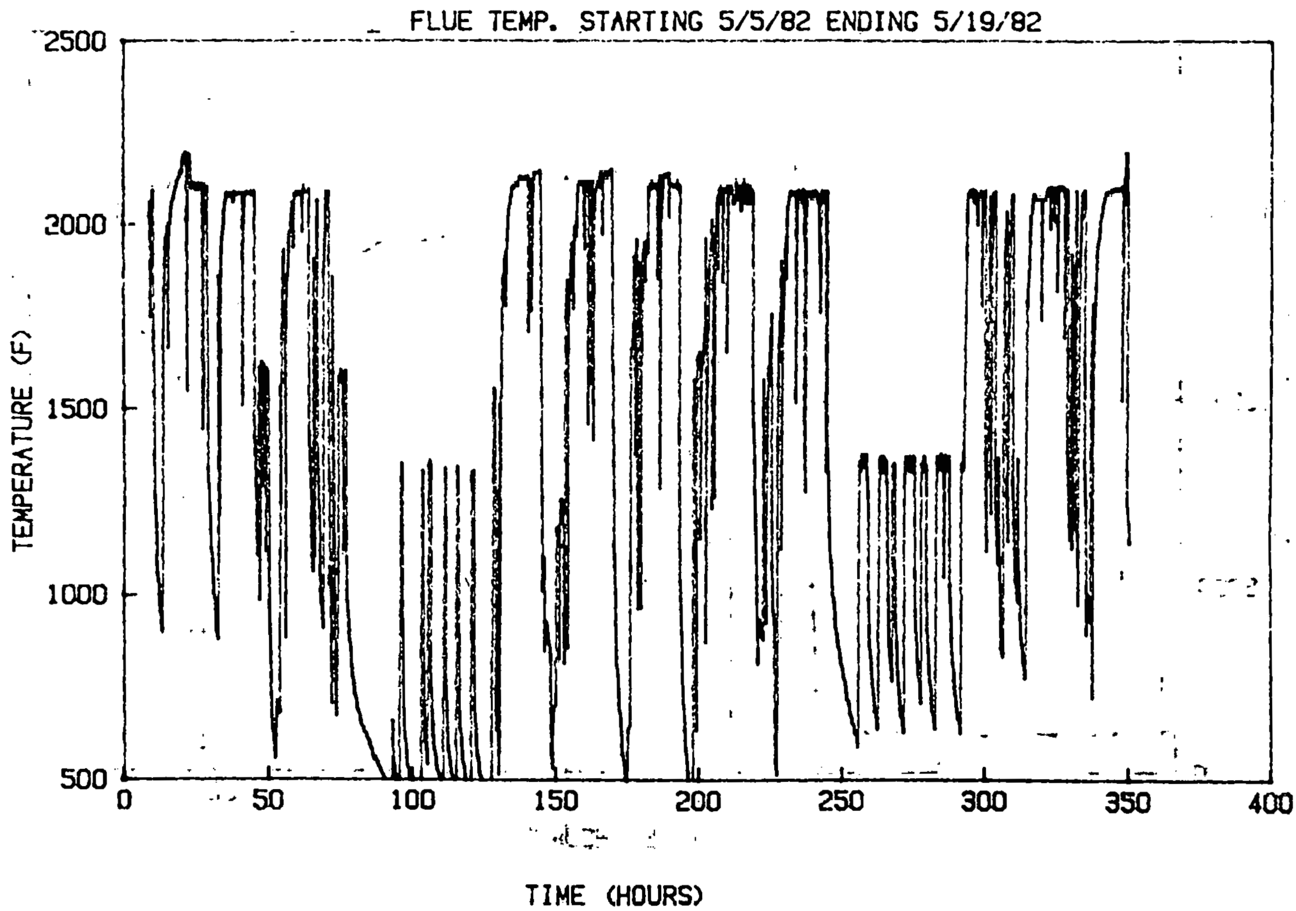

Figure 2.4 Flue Gas Temperature for a Typical Two Week Period

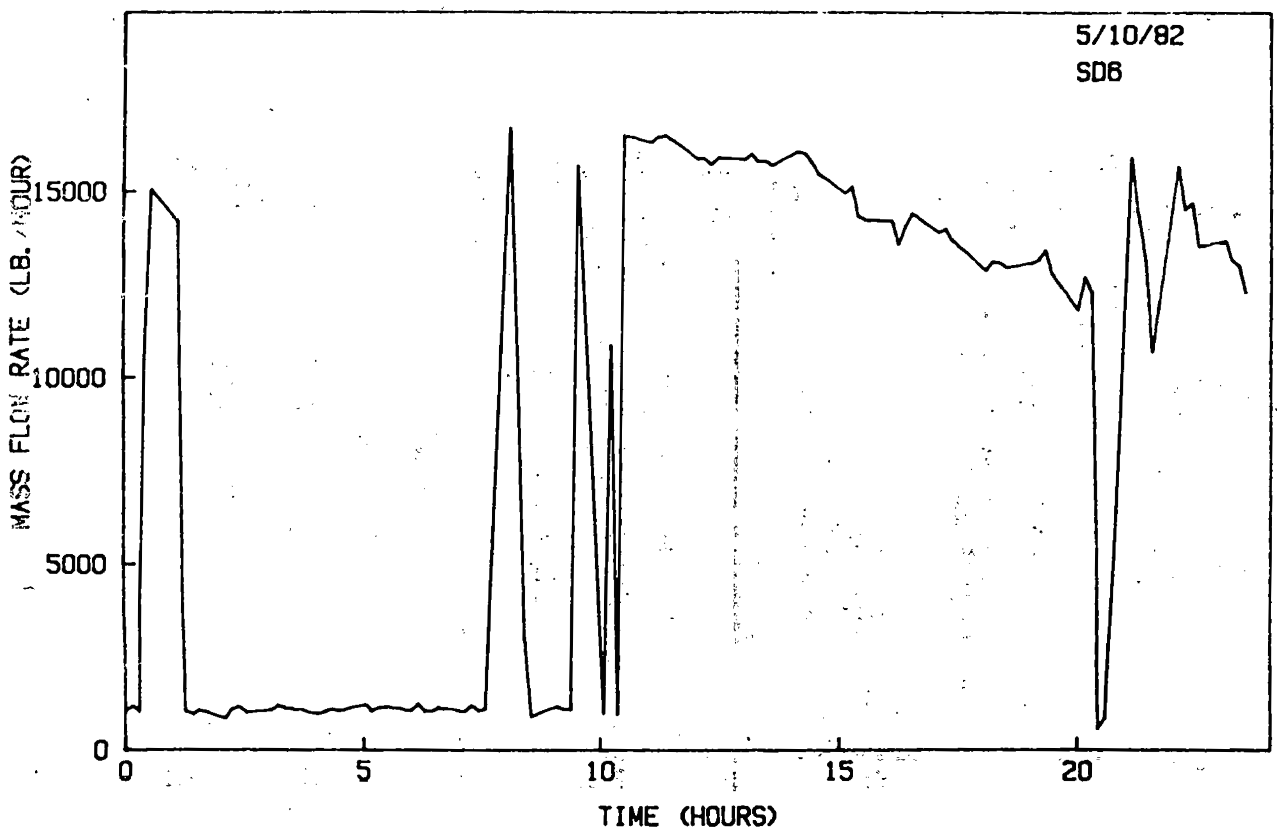

Figure 2.5 Total Combustion Air Flow Rate

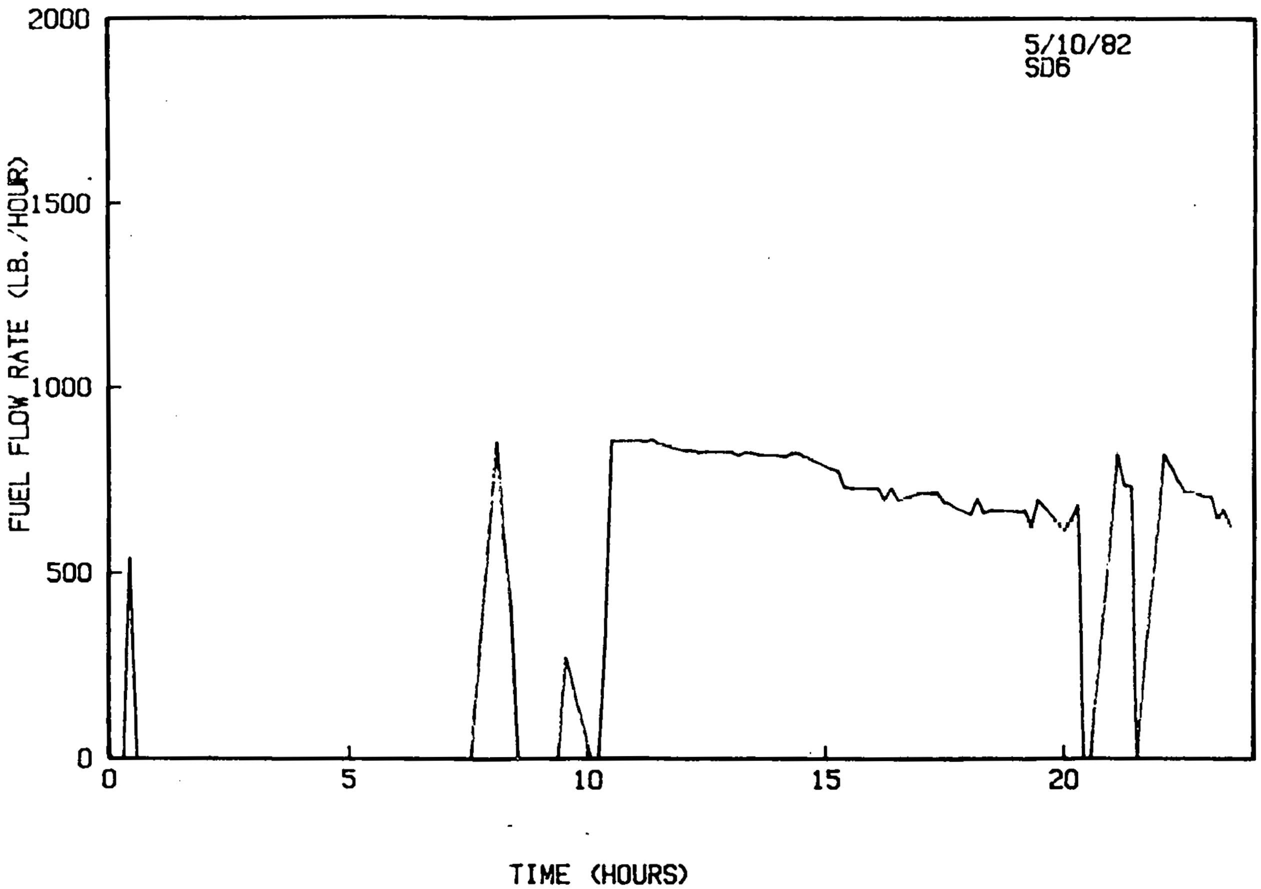

Figure 2.6 Total Fuel Flow Rate

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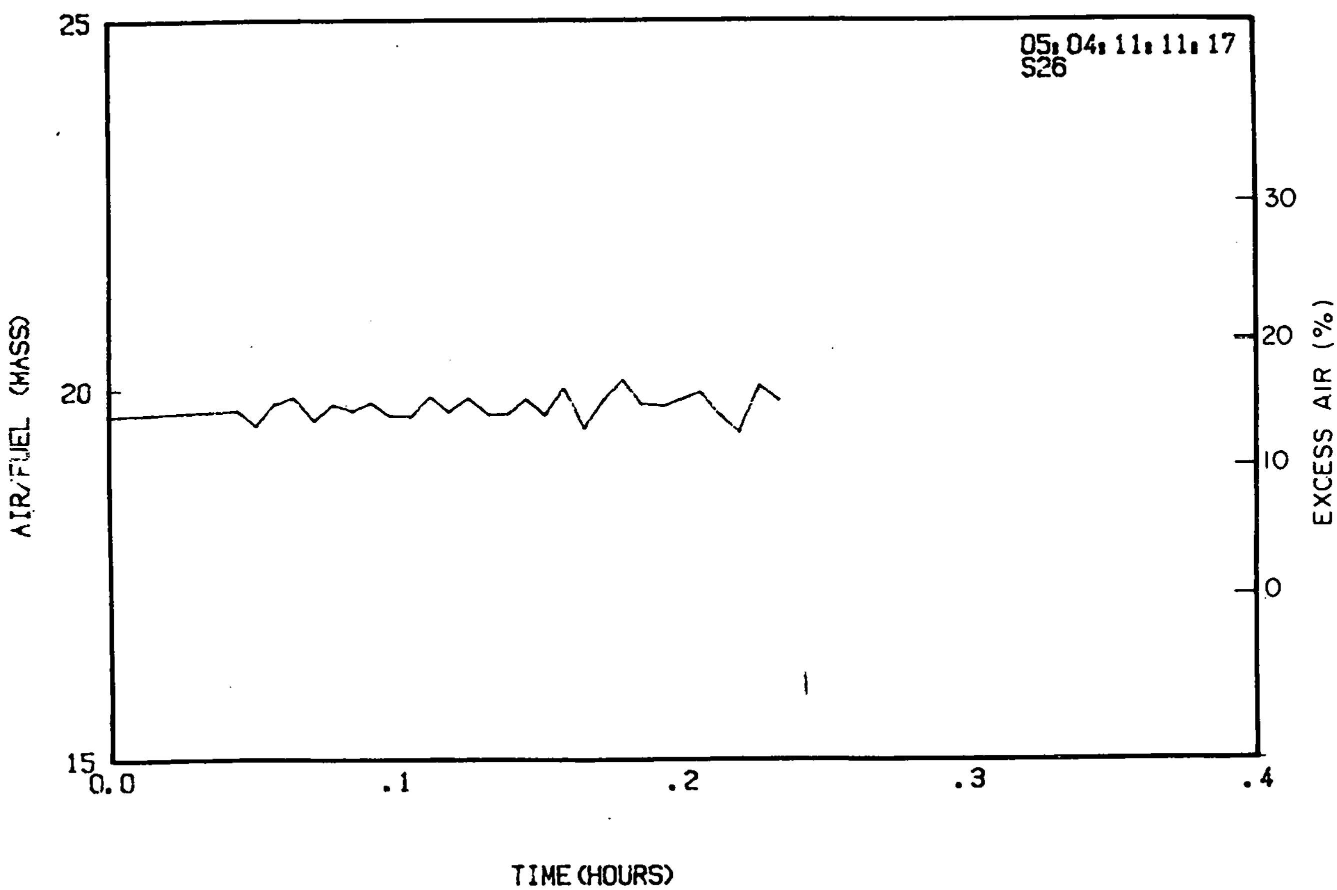

Figure 2.7 Air Fuel Ratio

recently been tuned. It has been observed that over a period of time burner valve settings will drift causing an increase in flow rate. Figures 2.8 and 2.9 show the air and fuel flow rates, respectively, for such conditions. The total flue gas flow rate is 5.4 lbm/sec, a 12-percent increase over the tuned burners.

2.2.3 Flue Gas Temperature

Figure 2.10 shows the flue gas temperature to be approximately constant at 2200°F during the charging cycle. During standby, when scrap charging is not occurring (0 to 10 hours of Figure 2.10), the measured flue gas temperature was below 500°F. However, the thermocouple measuring the flue gas temperature is located close to the air jet damper. When the burners are shut off, it is possible for the cold air from the damper to convectively cool the thermocouple resulting in a temperature reading lower than the actual flue gas temperature.

The value of the flue gas temperature cannot be correlated to burner flow rate alone. It is dependent on the difference between the heat entering the furnace from the burners (controlled by the operator and automatic controls) and the heat being absorbed by the scrap (controlled by the scrap feed rate). Wall losses can be ignored as being small and relatively constant. In Figure 2.11, after about 14 hours, the firing rate is decreasing in response to the completion of the scrap feed. However, the melt temperature is rising and hence is absorbing less heat. Thus the flue gas temperature remains constant.

After completion of scrap melting, the operator will frequently reduce the firing rate by reducing one or both of the temperature settings. Beyond 7 hours on Figure 2.12 the flue gas temperature setting was reduced to 1400°F and the melt temperature was set to some value above 1250°F. Now the burners are firing only as necessary to satisfy the flue gas temperature setting.

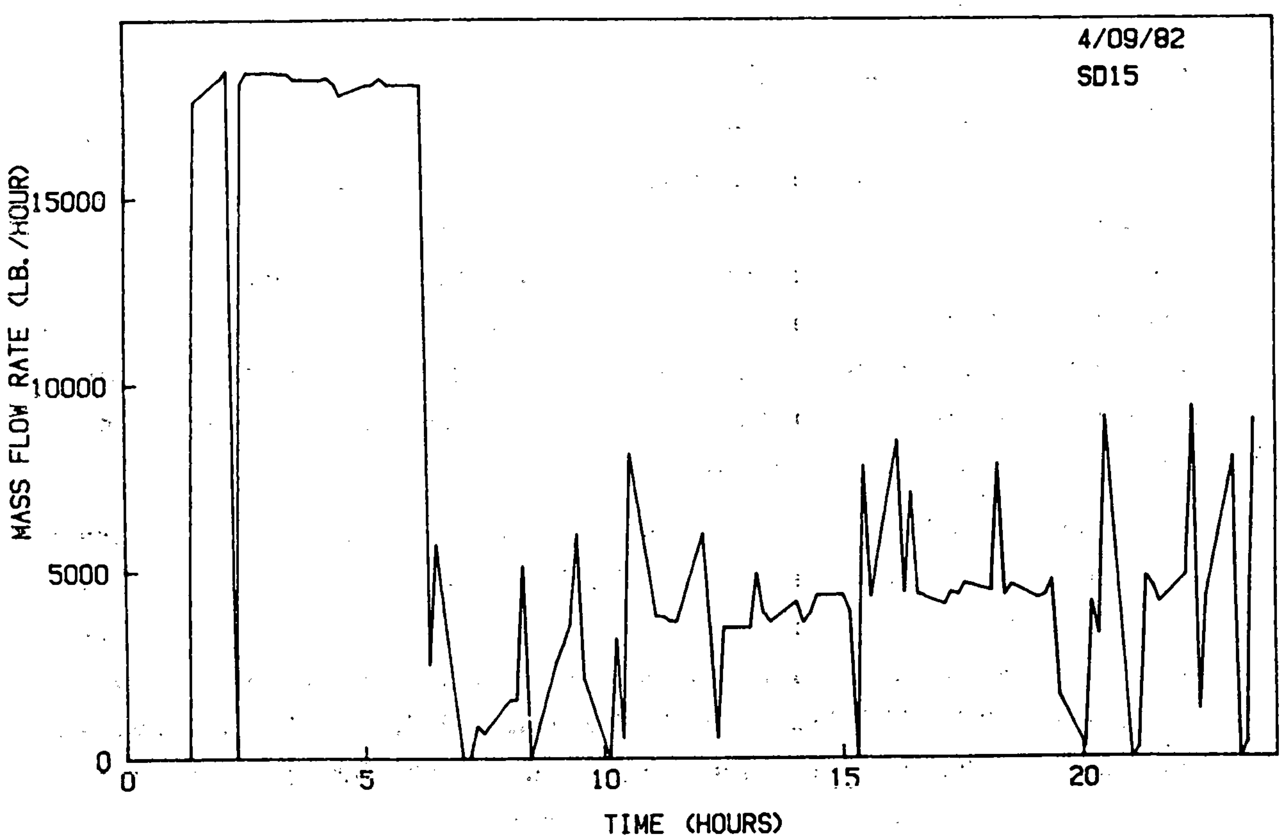

Figure 2.8 Total Combustion Air Flow Rate for Untuned Burners

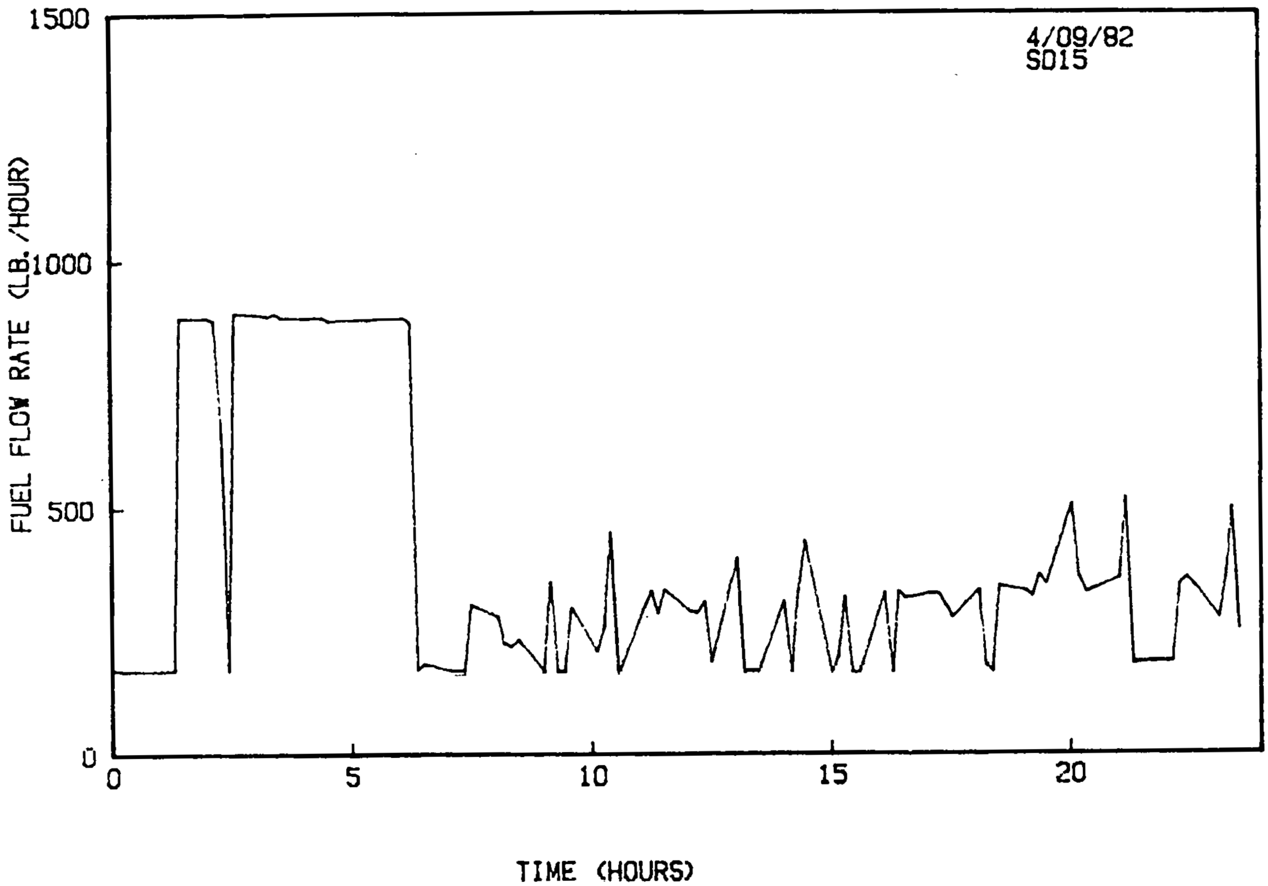

Figure 2.9 Total Fuel Flow Rate for Untuned Burners

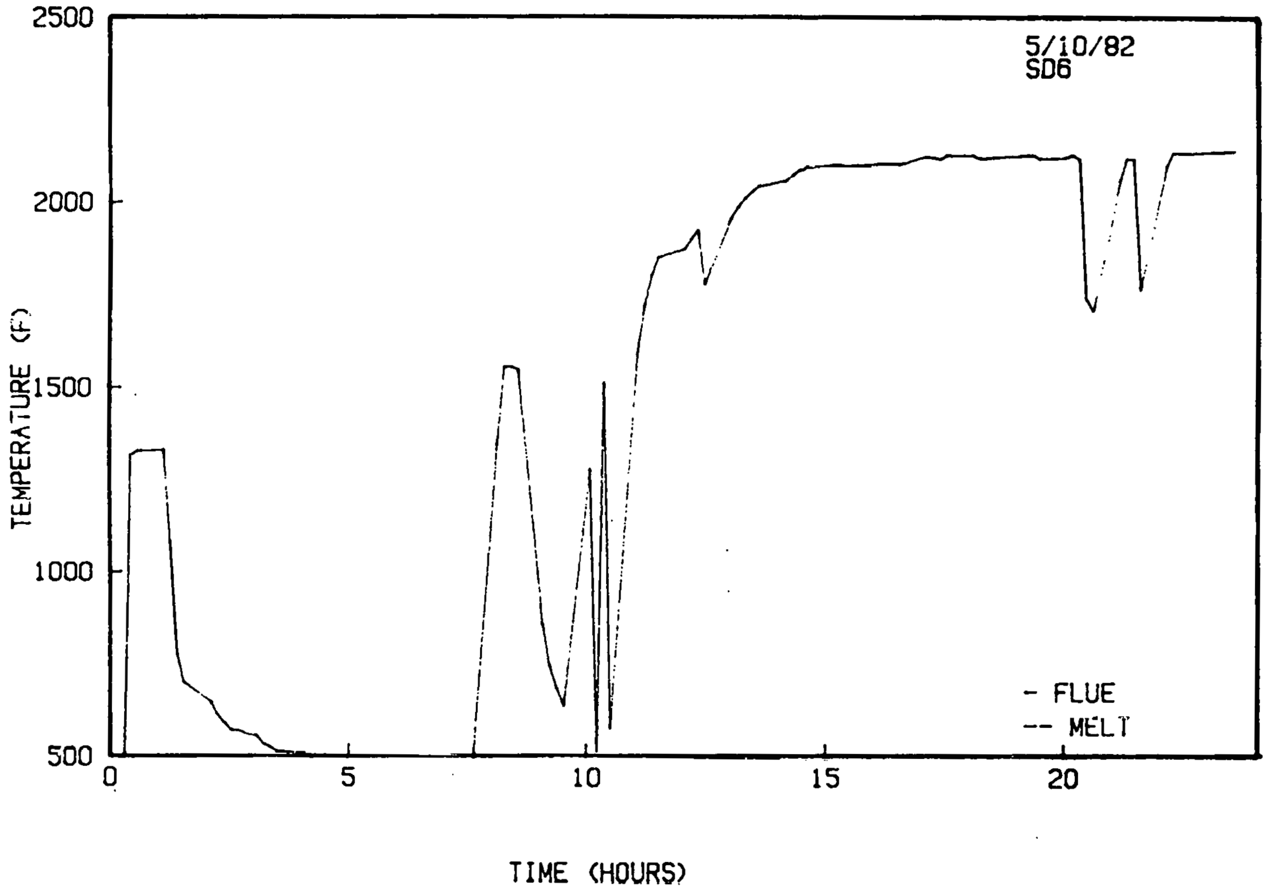

Figure 2.10 Measured Flue Gas Temperature

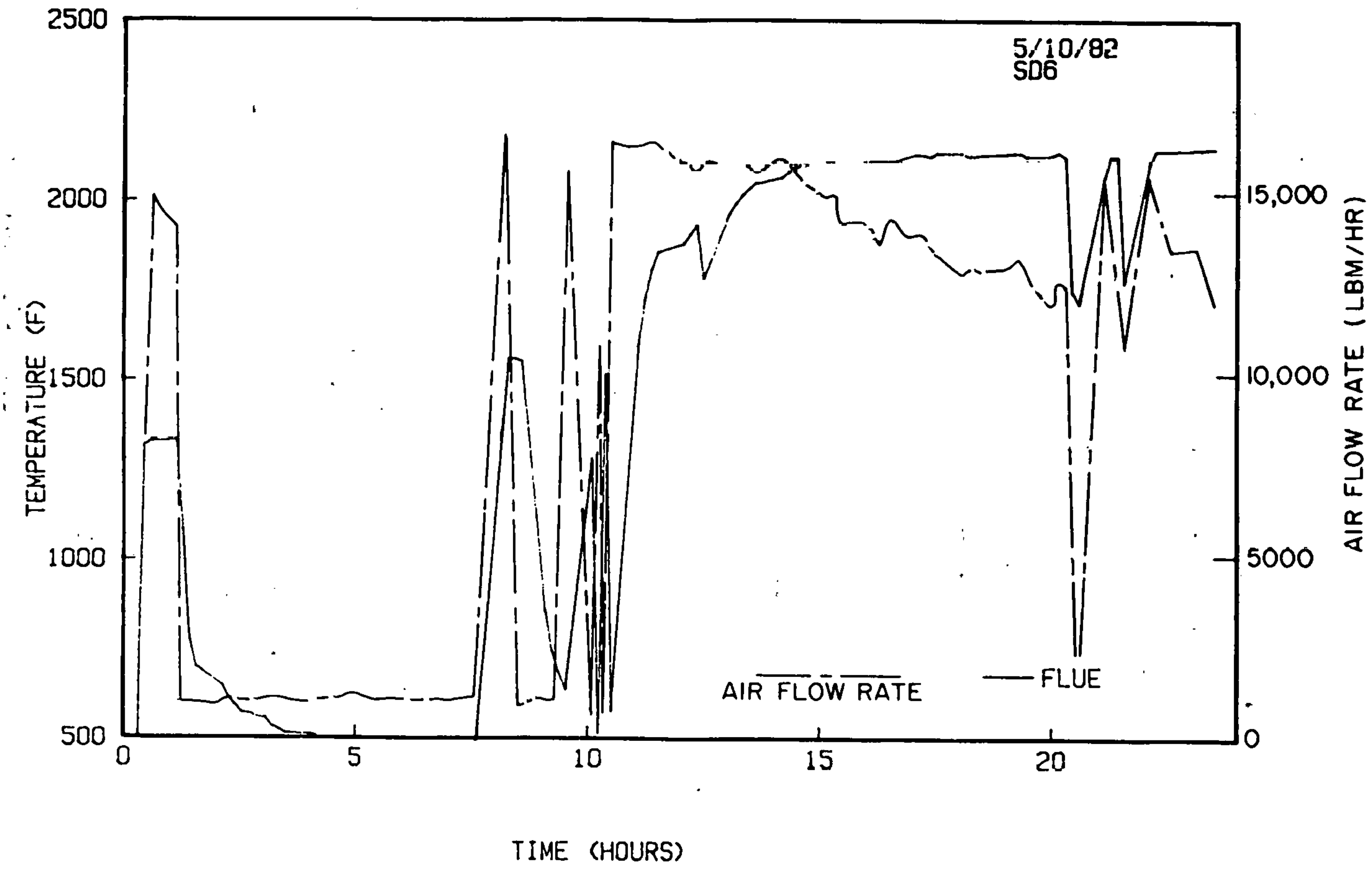

Figure 2.11 Flue Gas Temperature Variation with Flow Rate

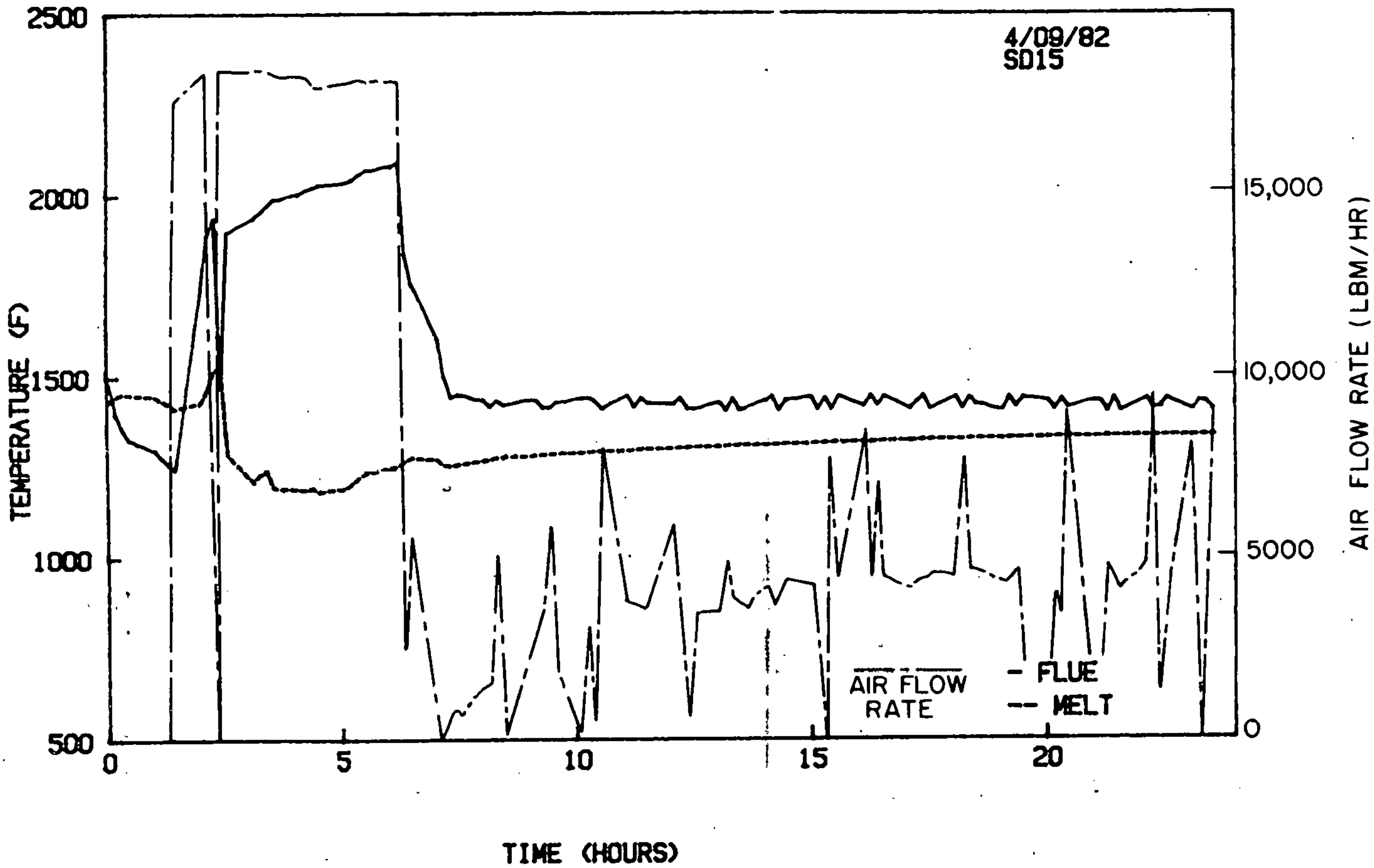

Figure 2.12 Flue Gas and Melt Temperature Variation with Flow Rate

The flow rate and temperature response to a step change in the valve settings can be observed in Figure 2.13. At about 0.225 minutes, the air and fuel flow valves were closed by the controller. The air and fuel flow rates then simultaneously decreased in a step-wise fashion. At that point, the flue gas temperature began to decay. The proportional and step-wise controls described are typical of the VMC operation.

Also shown in Figure 2.13 are the fluctuations in the nominal flow rate brought about by the control system. The fluctuations are minimal, about ±95 lbm/hr or ±1½ percent.

2.3 FURNACE ENERGY USAGE ANALYSIS

An energy balance on the furnace, based on the data gathered by the data acquisition system, was calculated. The energy input to the furnace is known from the measured air and fuel flow rates. Three additional assumptions are used:

1. Stack losses. The flue gas flow rate is assumed to be equal to the sum of the air and fuel flow rates. Leakage is ignored. The flue gas temperature is measured; hence, the flue gas energy can be calculated.

2. Energy used to melt the aluminum scrap. This is composed of two parts: the sensible heat needed to raise the scrap from room temperature to melting temperature, and the latent heat of fusion of the scrap. Since the melt temperature and scrap feed are known, both components can be determined.

3. Wall losses. This is taken as the difference between the energy input and the sum of 1 and 2 above.

Figures 2.14 through 2.17 show the energy balance, during the charging cycle, for four typical days. Of the total energy input of 14 to 18 MMBtu/hr only 2.3 to 3.3 MMBtu/hr is needed to melt the scrap for an overall efficiency of 13 to 23 percent. The efficiency is somewhat lower

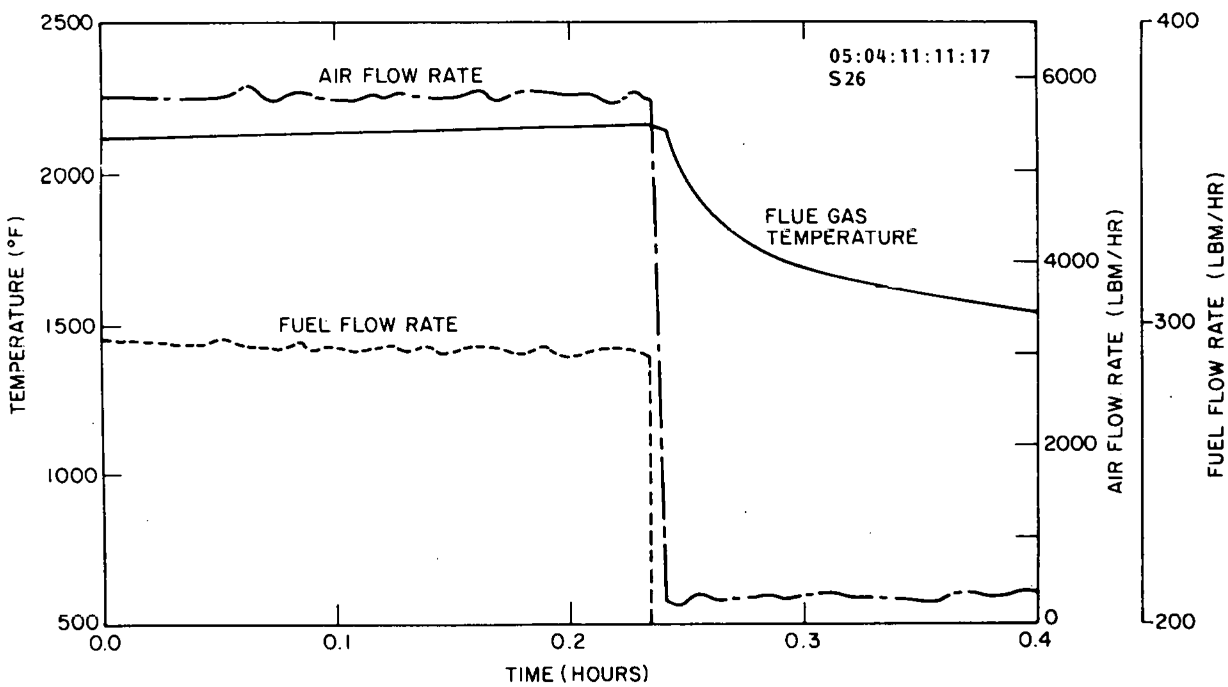

Figure 2.13 Effect of Changes in Valve Setting on Flue Gas Temperature and Air and Fuel Flow Rates

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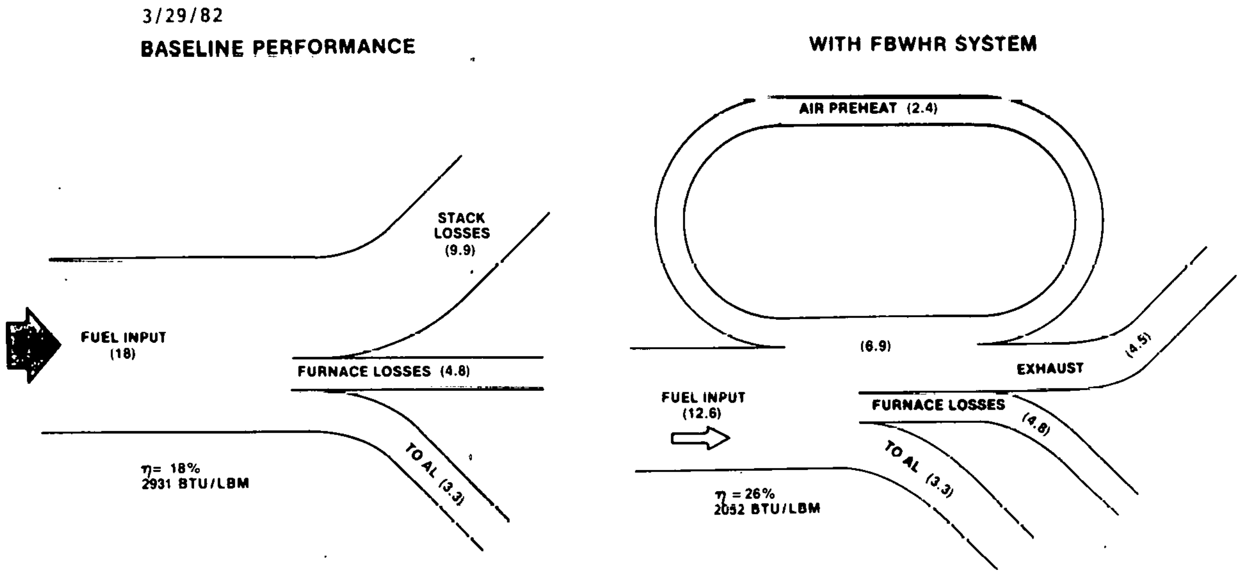

Figure 2.14 Heat Balance on Furnace #OH2 at Maximum Firing Rate (MMBtu/hr)

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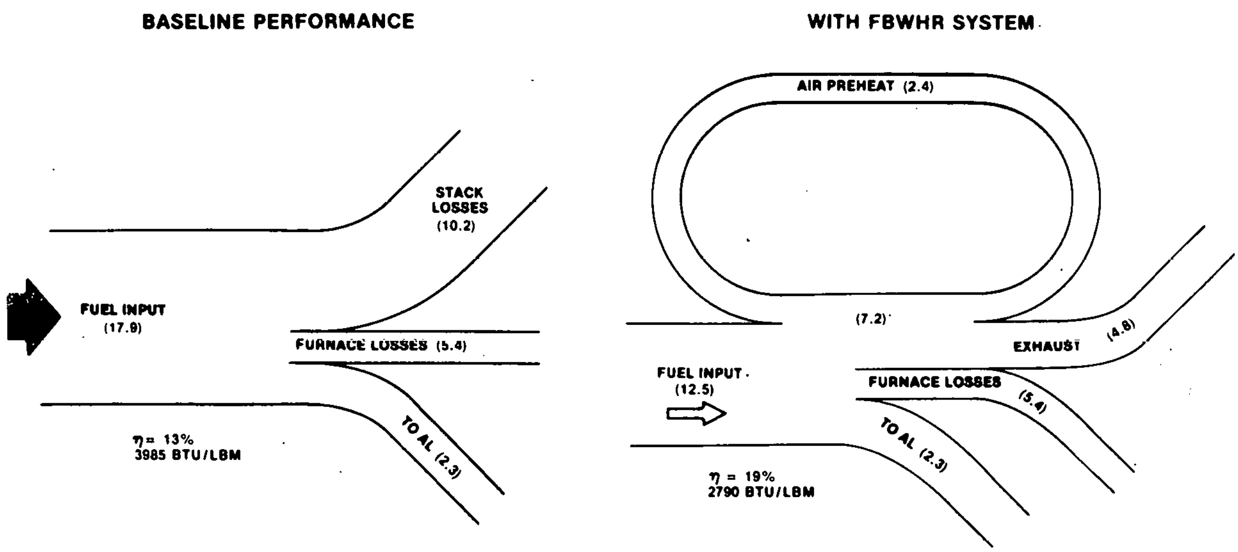

Figure 2.15 Heat Balance on Furnace #OH2 at Maximum Firing Rate (MMBtu/hr)

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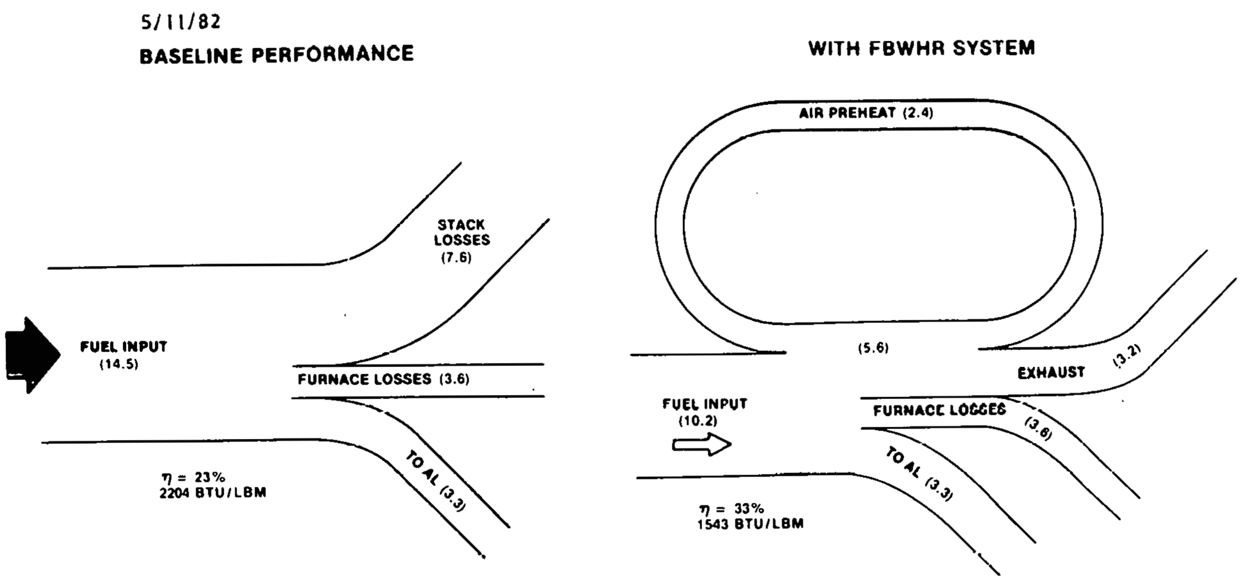

Figure 2.16 Heat Balance on Furnace #OH2 at Maximum Firing Rate (MMBtu/hr)

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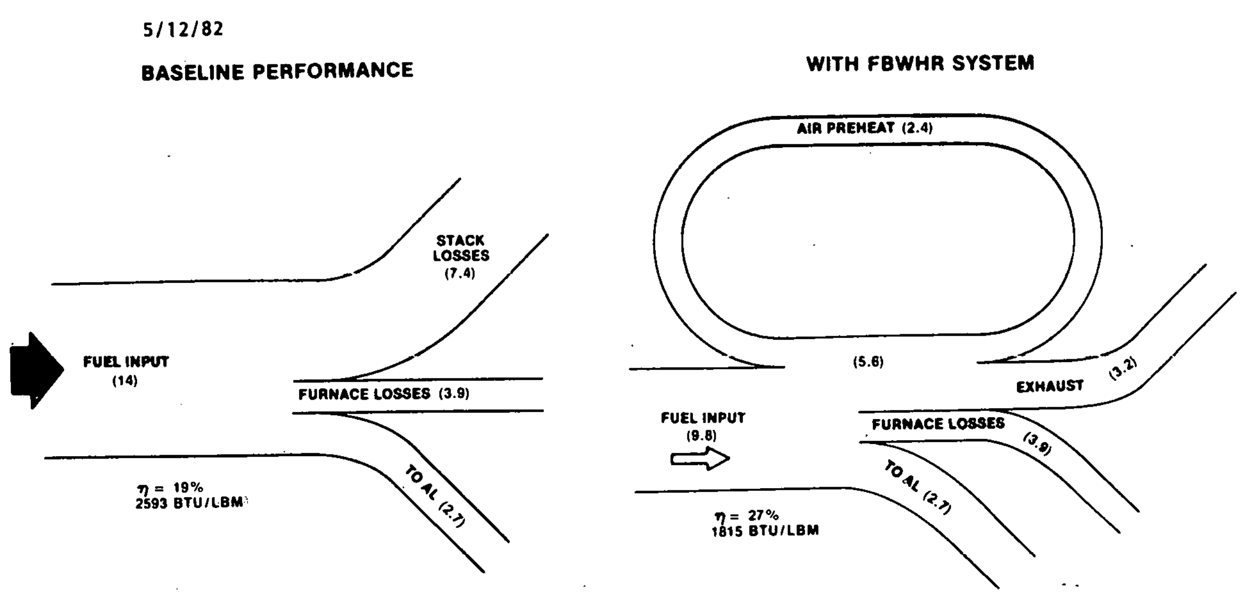

Figure 2.17 Heat Balance on Furnace #OH2 at Maximum Firing Rate (MMBtu/hr)

than the design value. This is possibly due to the current difficulties VMC is experiencing with their chlorinating system. In order to complete the chlorinating process it is required at times to keep the burners at high fire longer than is necessary to melt the scrap.

Of the balance of the heat, 3.6 to 5.4 MMBtu/hr are exhausted in the flue gases. Thus, about 55 percent of the total heat input is lost in the exhaust gases.

2.4 FURNACE TURNDOWN

Furnace turndown is defined as the ratio of maximum to minimum furnace flow rates encountered during normal operation. It is necessary to know the furnace turndown and the energy contained in the turndown in order to determine the required turndown of the recuperator. The first step is to determine the amount of time the furnace spends at each flow rate; this is shown in Figure 2.18. The combustion air flow rate is plotted as a function of the percent of time spent at that flow rate. The data are averaged for two 19-day periods; one before the burners were tuned (solid line) and one after (dashed line). For each condition, about 40 percent of the time is spent at high fire. At a flow turndown of 2:1 (one half of the maximum flow rate) the cumulative amount of time spent is 55 percent for the tuned case and 50 percent for the untuned case.

The flue gas energy content during turndown is of considerable importance since it determines the economy of the system. It can be calculated from the flow rates of Figure 2.18 and from the measured flue gas temperatures. The results are shown in Figure 2.19. About 80 percent of the available flue gas energy is contained in the high fire flow rate. Well over 90 percent of the energy is represented at a turndown of 2:1. The recuperator, then, should be capable of operating at half the design flow rate. Operation below this level would produce only a marginal increase in energy savings.

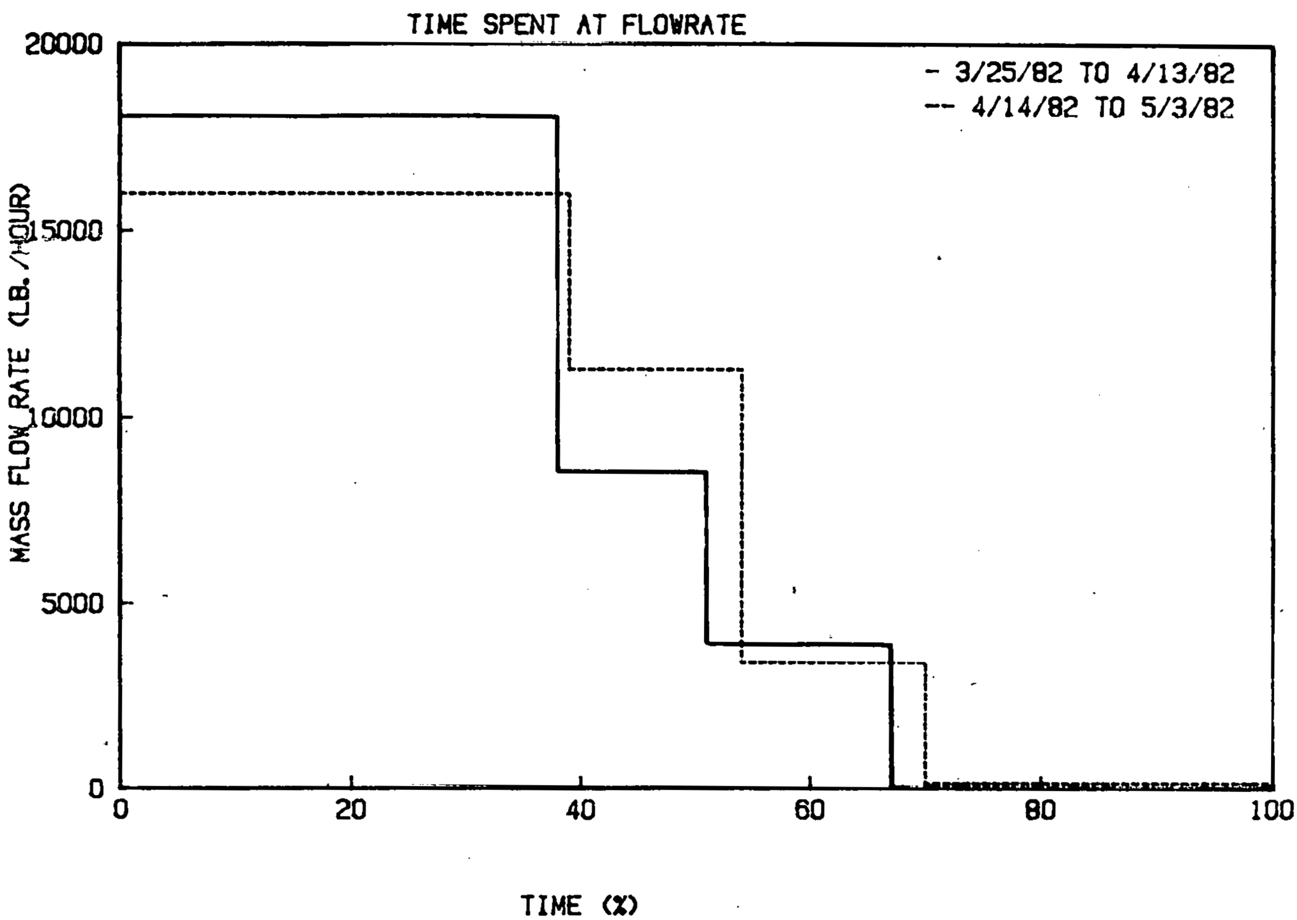

Figure 2.18 Time Spent at Turndown

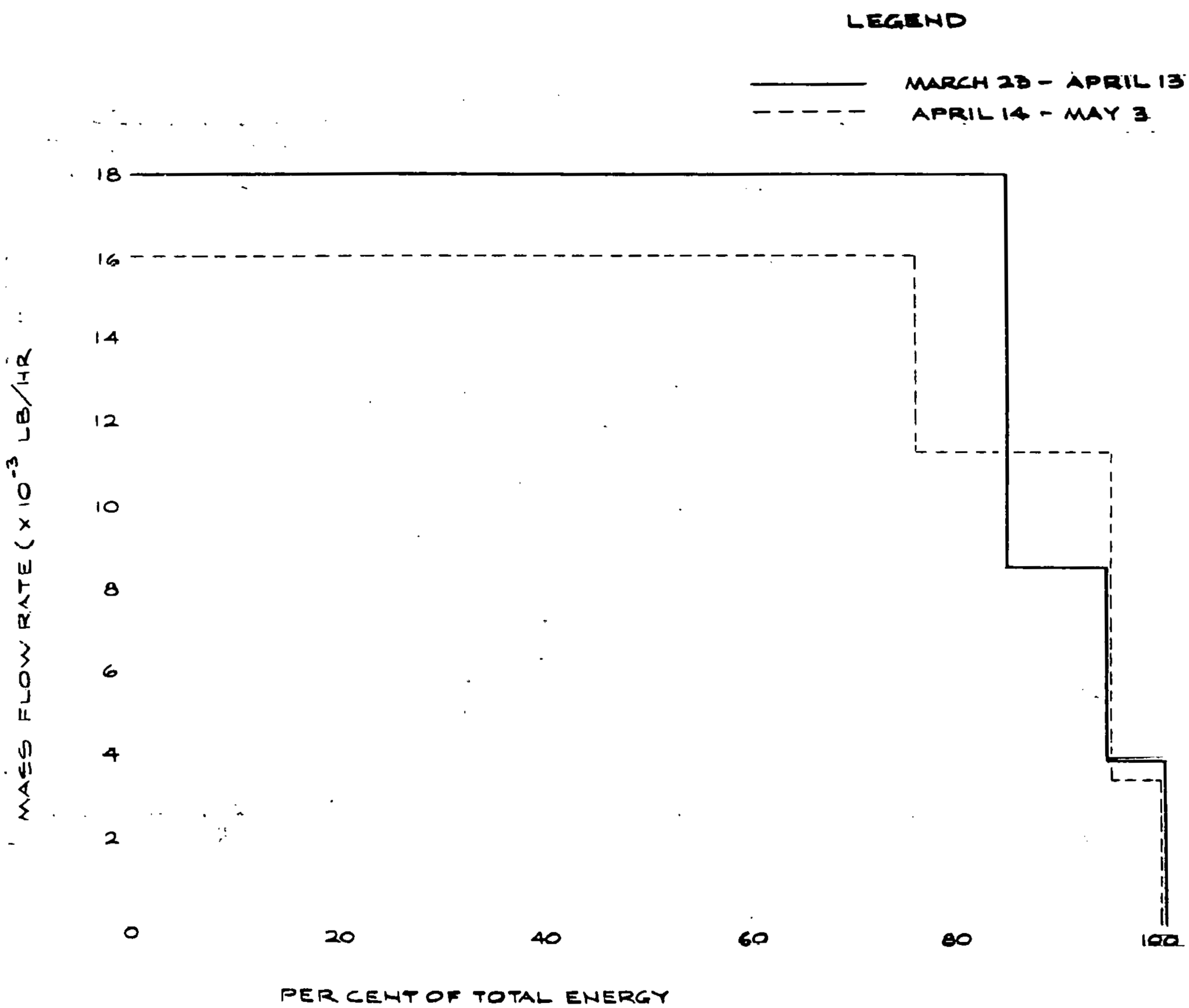

Figure 2.19 Energy Turndown

3. CONCEPTUAL DESIGN

This section describes the conceptual design of the fluidized-bed waste-heat recovery system for the VMC site. The fluidized-bed operating conditions necessary for successful furnace operation have been determined and limitations established in Chapter 2. In this chapter, the system sizing and media selection is presented as well as the concept for off-design operation.

3.1 SYSTEM CAPACITY

The FBWHR system flow rate and temperature specifications can be accurately predicted based on the measured furnace data and on proven analytical procedures. The analytical procedures determine the effect the recuperator has on the furnace measured data. For instance, the effect of preheating the combustion air is to reduce the burner fuel and air requirements needed to produce a given furnace heat flux input. The analytical procedures are conducted by first constructing an energy balance around the furnace-recuperator combination and, second, by knowing the fluidized-bed characteristics. The results, in terms of the furnace total mass and volume flow rate change, are given in functional form as:

$$\frac{\Delta \dot{m}}{\dot{m}} = 1 - \frac{f(T_A)}{f(T_A')}$$

$$\frac{\Delta \dot{v}}{\dot{v}} = \frac{f(T_A)}{f(T_A')} \frac{T_A'}{T_A} - 1$$

where:

$\frac{\Delta \dot{m}}{\dot{m}}$, $\frac{\Delta \dot{v}}{\dot{v}}$ = change in burner mass and volume flow rate, respectively

T_A = preheat combustion air temperature

T_A' = unpreheated combustion air temperature

The results are given in Figure 3.1. As the preheated air temperature is increased, the total burner air flow rate and, hence, fuel flow rate is reduced. At the design preheat temperature of 1000°F, a 30 percent reduction in fuel flow rate occurs. This results in a design flow rate of 3.4 lbm/sec. In order for the FBWHR system to pass this flow and remain within the fluidized-bed design criteria, a bed cross-sectional area of 20 ft^2 is required.

The heat balance for the aluminum furnace with the recuperator is shown in Figures 2.13 through 2.17. At the maximum firing rate, the FBWHR system recovers 2.4 MMBtu/hr from the exhaust gases and uses it to preheat the combustion air. This reduces the required fuel input from 18 to 12.6 MMBtu/hr, a 30-percent reduction. The specific fuel consumption for the unrecuperated furnace is between 2200 and 4000 Btu/lbm. The recuperator reduces this to 1550 to 2000 Btu/lbm.

The recuperator flow rates and temperatures at the design point are shown in Figure 3.2. The combustion air is preheated from 100°F to 1000°F at a flow rate of 146,000 scfh. The heat provided to this combustion air is taken from the exhaust gases where the temperature is reduced from 2000°F to 1250°F at a flow rate of 160,000 scfh.

The amount of flue gas exiting the furnace may become greater than the design value due either to air leakage into the furnace or off-design burner flow rates. Off-design flow rates of as much as 15 percent have been observed. Generally, the FBWHR system will not be affected by these off-design flows. However, it is possible for these flows to periodically increase to higher values or for air leakage into the furnace to occur so that the flue gas flow rate may become substantially higher than the design value. Further, the amount of this excess flow will vary with furnace operation and cannot be accurately predicted. To accommodate this increased flow, a flue gas bypass will be provided on the FBWHR system, as shown in Figure 3.2, that will automatically divert the excess flow.

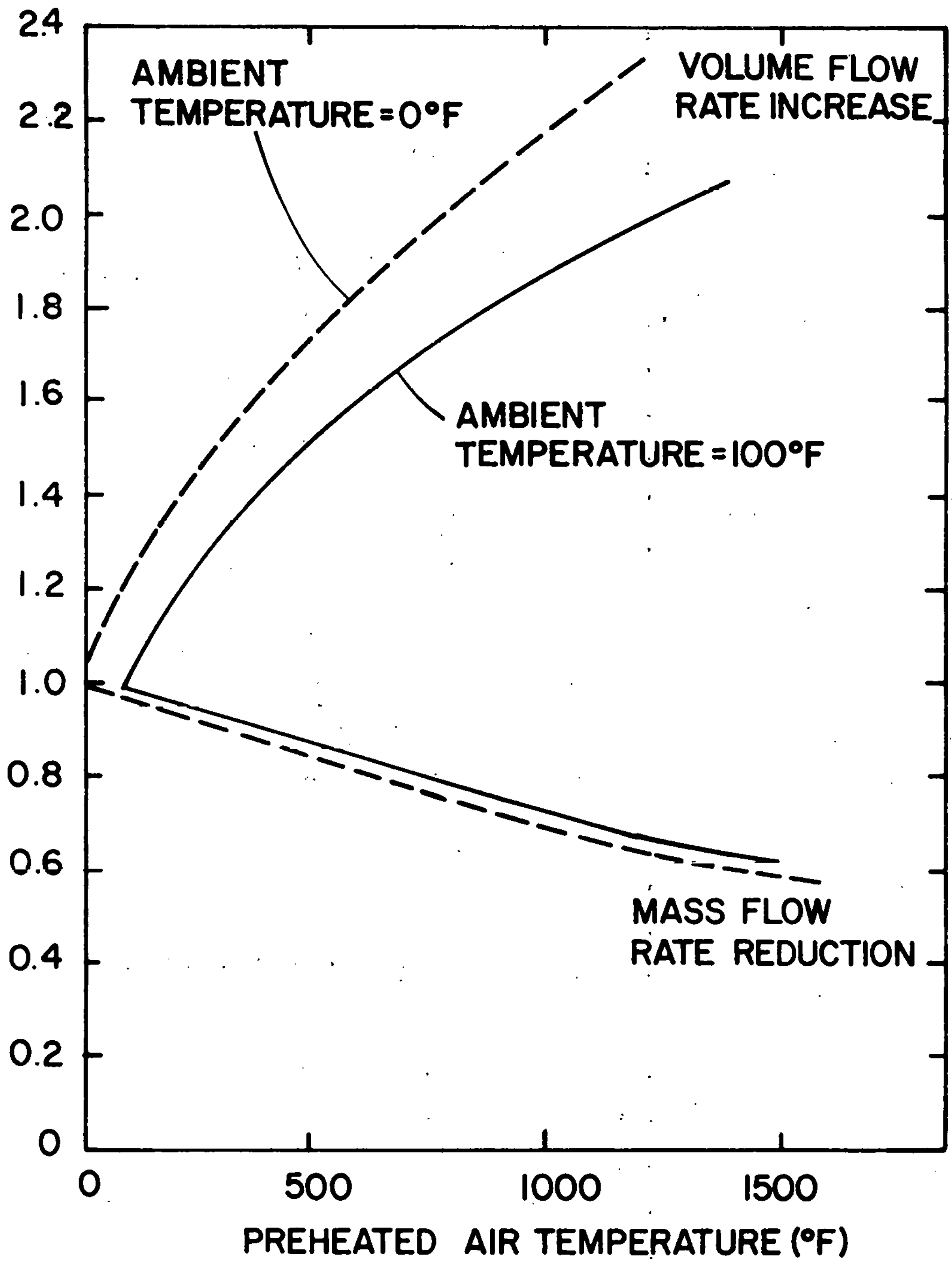

Figure 3.1 Effect of Recuperator on Furnace Flow Rate

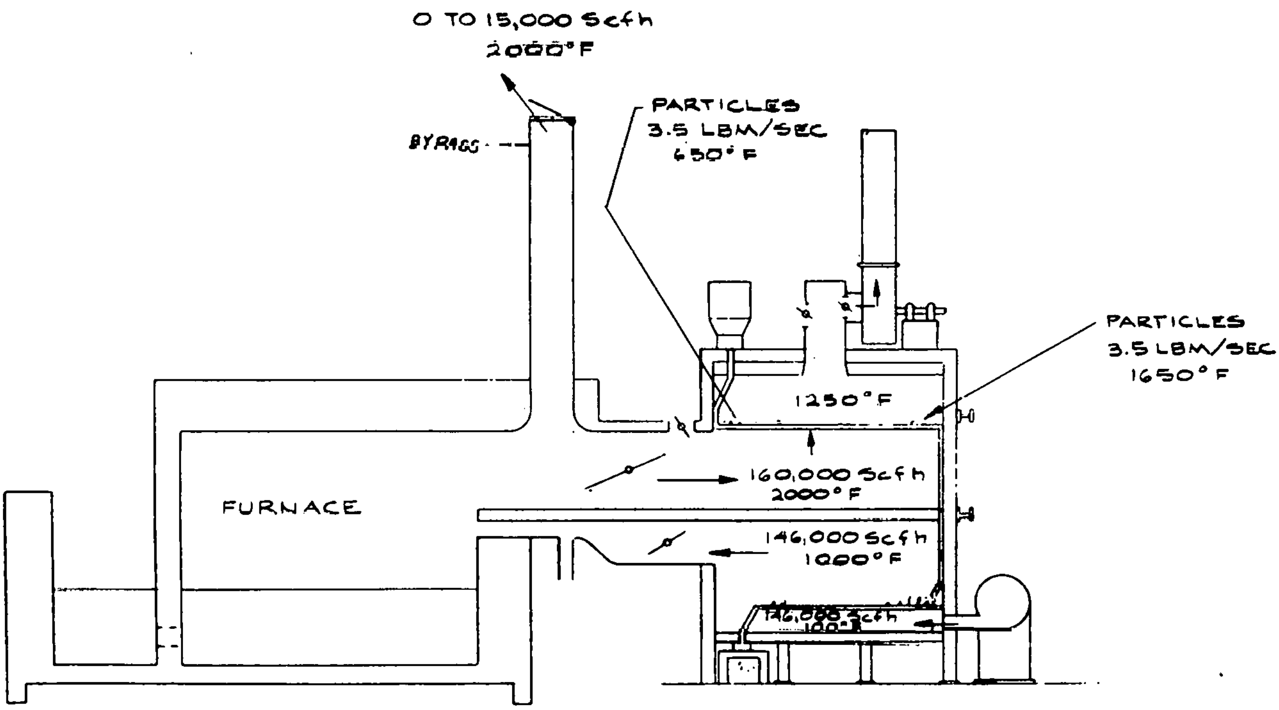

Figure 3.2 Recuperator Flow Rates and Temperatures

3.2 RECUPERATOR TURNDOWN

Recuperator turndown is defined as the ratio of the highest to the lowest flue gas flow rate that can be passed through the recuperator without adversely affecting its performance. Turndown is important because it determines the amount of available flue gas energy that can be recovered. If the recuperator turndown is greater than or equal to the furnace turndown, all of the available flue gas energy will be recovered. However, since most of the flue gas energy is contained in the high-fire part of the cycle, it is possible for the recuperator turndown to be less than the furnace turndown and still capture a substantial part of the available energy. As shown in Section 2.4, a turndown of 2:1 will capture over 95 percent of the available flue gas energy.

In the FBWHR system, off-design operation can be handled by one of two methods. As the overall flow rate is decreased from the maximum, the fluidizing velocity can be allowed to decrease or the bed area can be decreased to maintain a constant fluidizing velocity

3.2.1 Fluidizing Velocity Turndown

In this fixed geometry concept, the percent open area of the distributor plates is such that the minimum pressure drop requirements across the distributor plates are satisfied at the required minimum flue gas flow rate.

The major advantage of this concept is that it can supply adequate turndown capability and yet it is inexpensive to fabricate, easy to operate, and requires little maintenance compared to other concepts.

The major problem in using the fluidizing velocity to control turndown is the high pressure drop needed at maximum firing conditions even when assuming a low velocity at low fire. The lowest velocity possible to maintain fluidization is the minimum fluidization velocity, which occurs when the drag force on the particles, caused by the gas passing upwards through the bed, is about equal to the weight of the particles.

Although it is theoretically possible to operate the FBWHR system at the minimum fluidization velocity, practical considerations require that the superficial velocity be appreciably increased. The primary consideration is to impart sufficient mobility to the particles to assure a smooth flow of solids away from the feed zone and along the bed. Laboratory tests simulating the FBWHR system operating conditions indicate that a velocity of three times the minimum fluidization velocity is required.

Using the criteria just explained, the minimum superficial velocity for a given temperature can be established and, therefore, the maximum superficial velocity that is acceptable can be calculated. If, for a given temperature and particle size, the minimum superficial velocity is 3 ft/sec and a turndown of 5 is necessary, the maximum superficial velocity would be 15 ft/sec.

Because the minimum pressure drop establishes the basis for the design, there has been a great deal of emphasis on this area in laboratory testing. From this testing, it was determined that the plate pressure drop must be at least one half of the bed pressure drop to maintain stability. For a 1-inch bed of the media selected, a distributor plate pressure of 0.75 in. wc is needed at low load conditions. Below this point, the bed will destabilize and results cannot be predicted.

A 1-inch bed depth was selected for the example as it is approximately the level that will be tenable for a production unit. Although the bed height could be decreased to reduce the overall minimum pressure drop, there is a point where the bed height itself sets the stability criteria. Laboratory tests suggest that operating at less than 1-inch bed depth in a production unit may be possible.

The major limitation to this concept is the relatively high pressure drop required at high fire. Since pressure drop is proportional to the square of the flow rate, a turndown of 5:1 would require a plate pressure drop, at high fire, 25 times greater than the minimum required. The total pressure drop (plate plus media) at high fire is plotted against turndown in Figure 3.3. A turndown of 2:1 requires a pressure drop of about 9½-in. wc; anything above that would be prohibitive.

3.2.2 Bed Area

The turndown of the system can be increased without a further increase in the system pressure drop by varying the bed area. This can be accomplished by separating the fluidized bed into two or more modules. As the flow rate of gases decreases, one or more modules would be shut off with the gases all going through the remaining modules, thereby reducing the flow area. It is, therefore, possible to operate at a high turndown with only a small variation (factor of two) in the superficial velocity.

If the temperature of the flue gases were constant at both high fire and low fire, the turndown of the system would vary directly with the area ratio. However, as is the case with many furnaces, the VMC furnace has a reduced flue gas temperature at low fire. In fact, the flue gas temperature drops over 600°F. The turndown capability is reduced due to the temperature effects on the pressure drop and the minimum superficial velocity. The net effect of the number of equally sized modules versus turndown, corrected for temperature, is shown in Figure 3.4. For example, an area ratio of 5 to 1 would yield a turndown of about 3 to 1 whereas without temperature correction the turndown expected would be 5 to 1. If module sizes were chosen by a geometric progression as shown in Figure 3.5, it would be possible to achieve the same turndown with fewer modules. This is also illustrated in Figure 3.4.

There are a number of problems with using the modular concept. The complexity of the system is such that further development will be needed to ensure that the maintenance level and costs are acceptable. Also, the gases in the nonoperating modules would be cooled allowing possibly corrosive agents to condense, which could result in serious materials problems.

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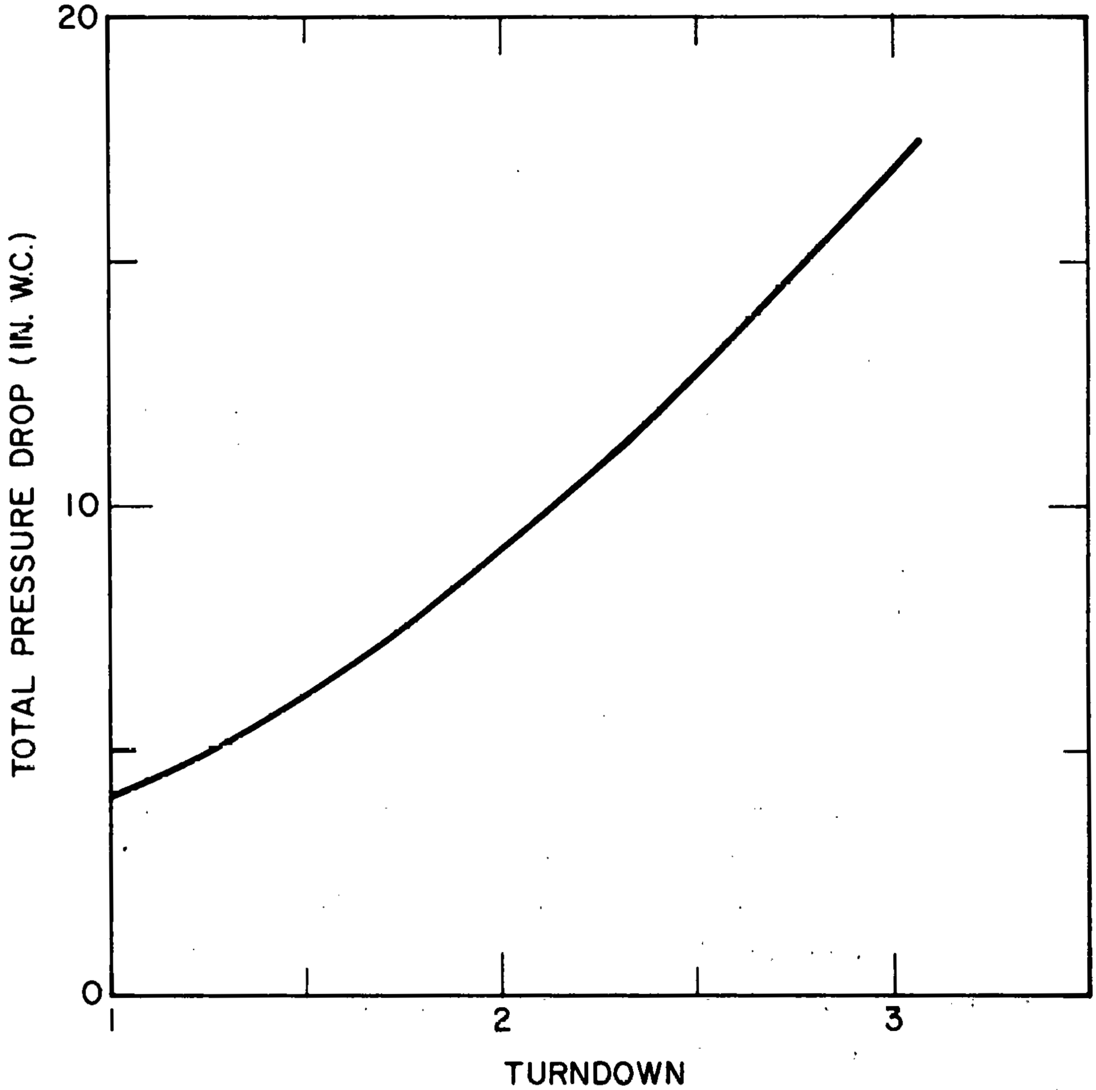

Figure 3.3 Effect of Turndown on Total Pressure Drop

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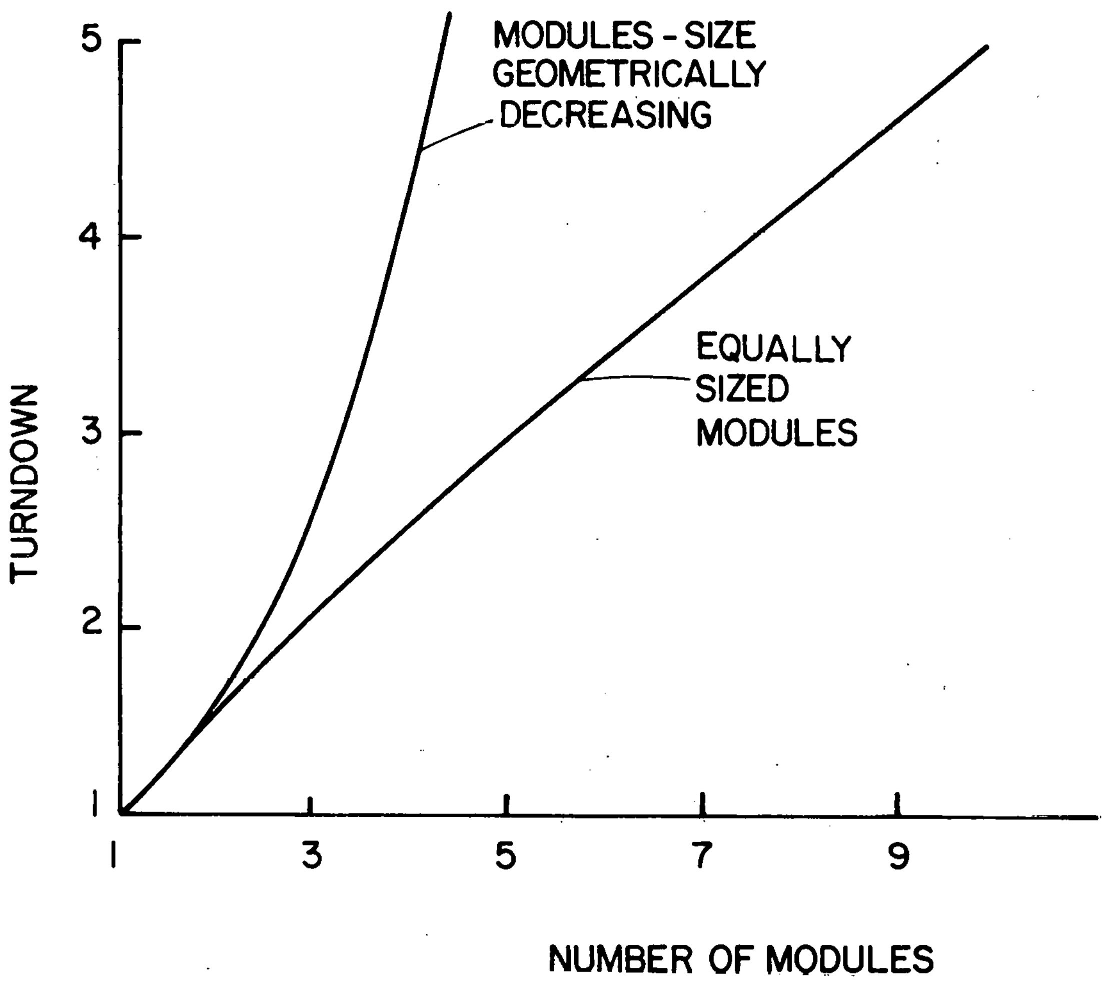
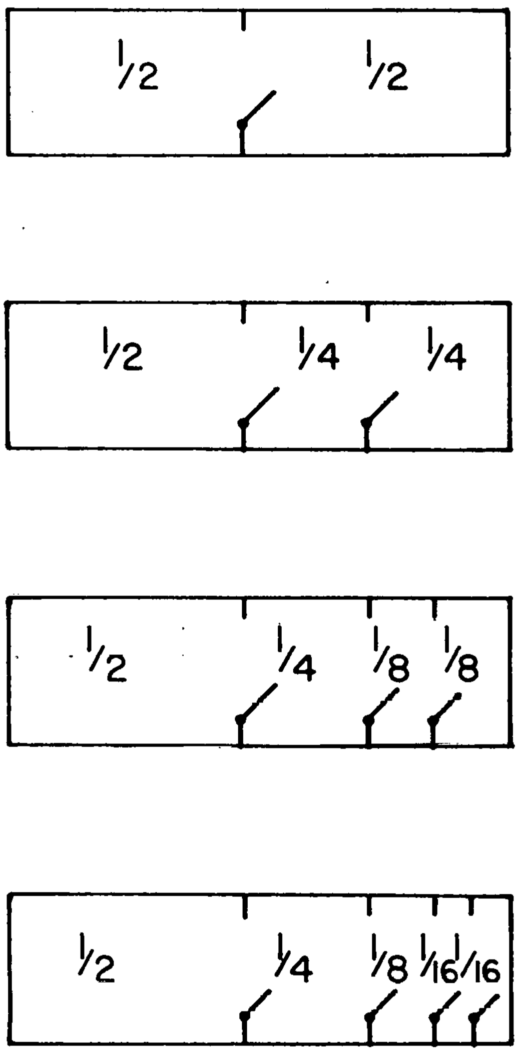


Figure 3.4 Turndown with Variable Bed Area



No. OF BEDS	AREA RATIO
2	2:1
3	4:1
4	8:1
5	16:1

Figure 3.5 Geometrically Varying Bed Area

3.2.3 Conclusions

Turndown for the VMC system will be effected by using the fluidized velocity option with a single bed. As mentioned in an earlier section, 95 percent of the potentially recoverable energy can be saved by a turndown of 2 to 1. This level of turndown can be reached with the fluidizing velocity variation.

The modular bed concept will not be used in this program because its higher turndown capability is not needed and because the effort to develop the concept would be considerable due to the corrosion problems and design complexity.

3.3 SYSTEM MEDIA SELECTION

Proper selection of the circulating heat transfer media for the FBWHR system is critical to assure optimum performance and minimum maintenance. Since the media will be continually circulated from the hot flue gases to the cool combustion air, high thermal shock resistance and low attrition of particles are of paramount importance. Equally important is the ability of the material to withstand the corrosive environment of the flue gas. Table 3.1 delineates the properties required of the heat transfer media. Although no material is ideal, the best material is alumina. Alumina is a hard ceramic that is readily available in a large variety of sizes, shapes, and purities.

The size of particles used in the FBWHR system influences both the size of the recuperator and the pressure drop requirements which in turn affects the cost of building and operating the system. From the heat exchanger characterization studies done in the previous reporting period, a bed depth of approximately 30 particle diameters is needed for the fluidizing gas to reach thermal equilibrium with the particles. This, combined with the stability criteria, shows that the distributor plate total pressure drop of the fluidized bed increases linearly with the particle diameter, as shown in Figure 3.6, resulting in an increasing

TABLE 3.1
MEDIA SELECTION CRITERIA

High Corrosion Resistance
Minimal Attrition Rate
Moderate Cost
Availability in Uniform Sizes
High Thermal Capacity
Compatibility with Process Furnace Exhaust
High Thermal Shock Resistance

operating cost. However, a larger particle size requires a higher fluidizing velocity which, with a constant mass flow rate of flue gas, results in a small distributor plate area as shown in Figure 3.7. This results in a decreasing fabrication cost.

The optimum particle size can be found by noting that the slope of the pressure curve is constant, while that of the area curve is not. Increasing the particle diameter yields a diminishing decrement in area yet requires a constantly increasing pressure drop. For this reason, it may not be useful to use a particle size greater than 800 μm.

A lower bound on the particle size is established based not only on the large recuperator size required but also on particle weepage through the distributor plate holes. To determine the minimum particle size, tests were performed with 660-μm particles and perforated plates with various hole sizes ranging from 1/16 to 1/8 in. in diameter. The tests indicated that while fluidized, particle weepage was insignificant. However, when the bed was stagnant a hole-size to particle-diameter ratio greater than 2.5 caused an unacceptably high weepage. Since hole size is limited to a minimum of 0.062 inch because of fabrication and fouling considerations, the smallest particle size that can be used is 630 μm. Thus, the media size is limited to the range from 630 to 800 μm.

In the laboratory studies, nonspherical alumina of 660 μm diameter and 95-percent purity was used. This selection was made essentially on the basis of economics. This low-grade material is readily available as blasting grain. There is some evidence that this material may not perform over a long period of time due to the impurities, cracks, and porosity within the particles. To assess the potential of this problem, photomicrographs of some alumina particles were taken by Oak Ridge National Laboratories. Figure 3.8 is a typical cross section of the particles enlarged 100x showing the various defects mentioned. Should these alumina particles break down in the recuperator, high-purity spherical alumina

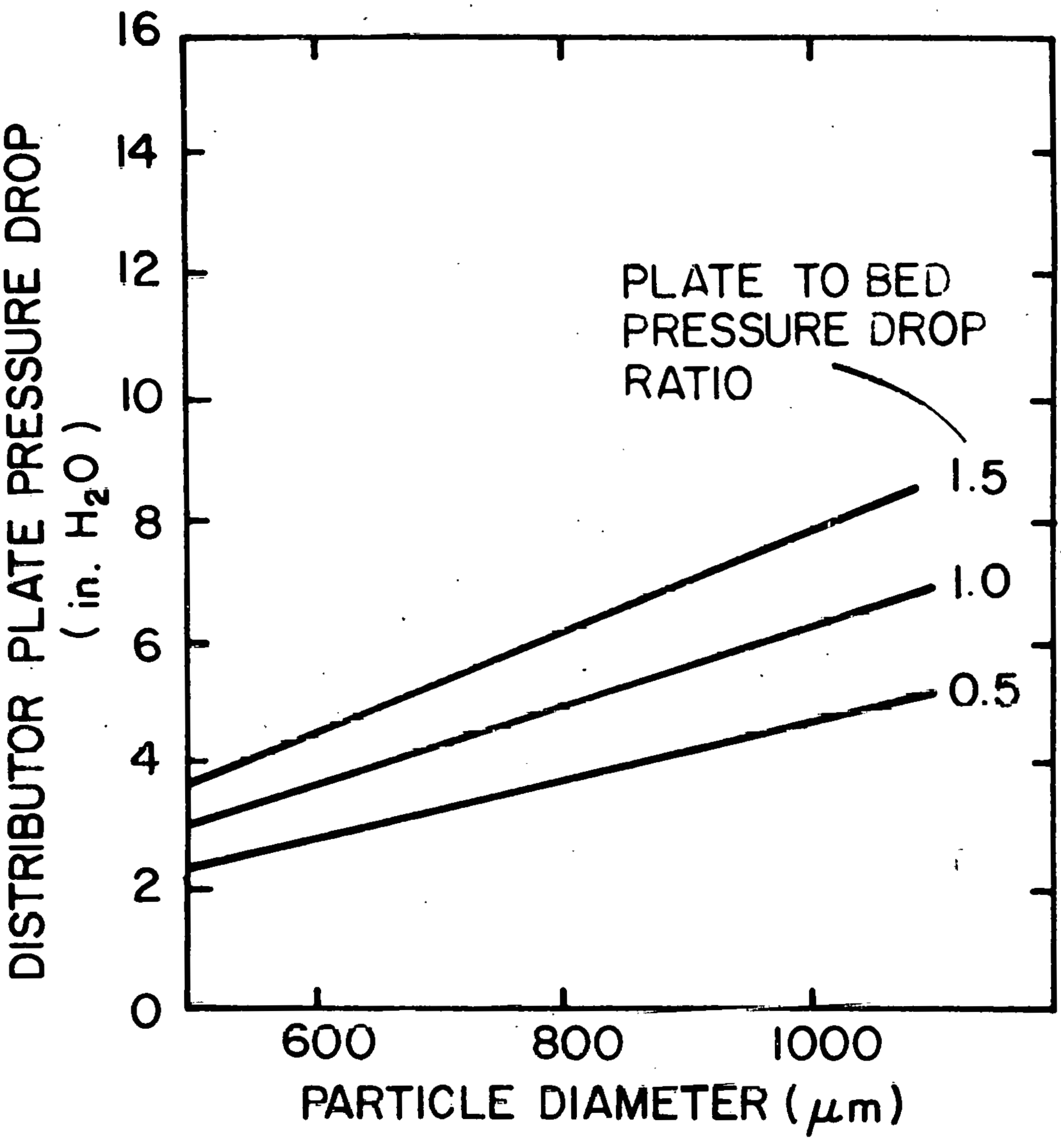


Figure 3.6 FBWHR System Size and Pressure Drop Dependence

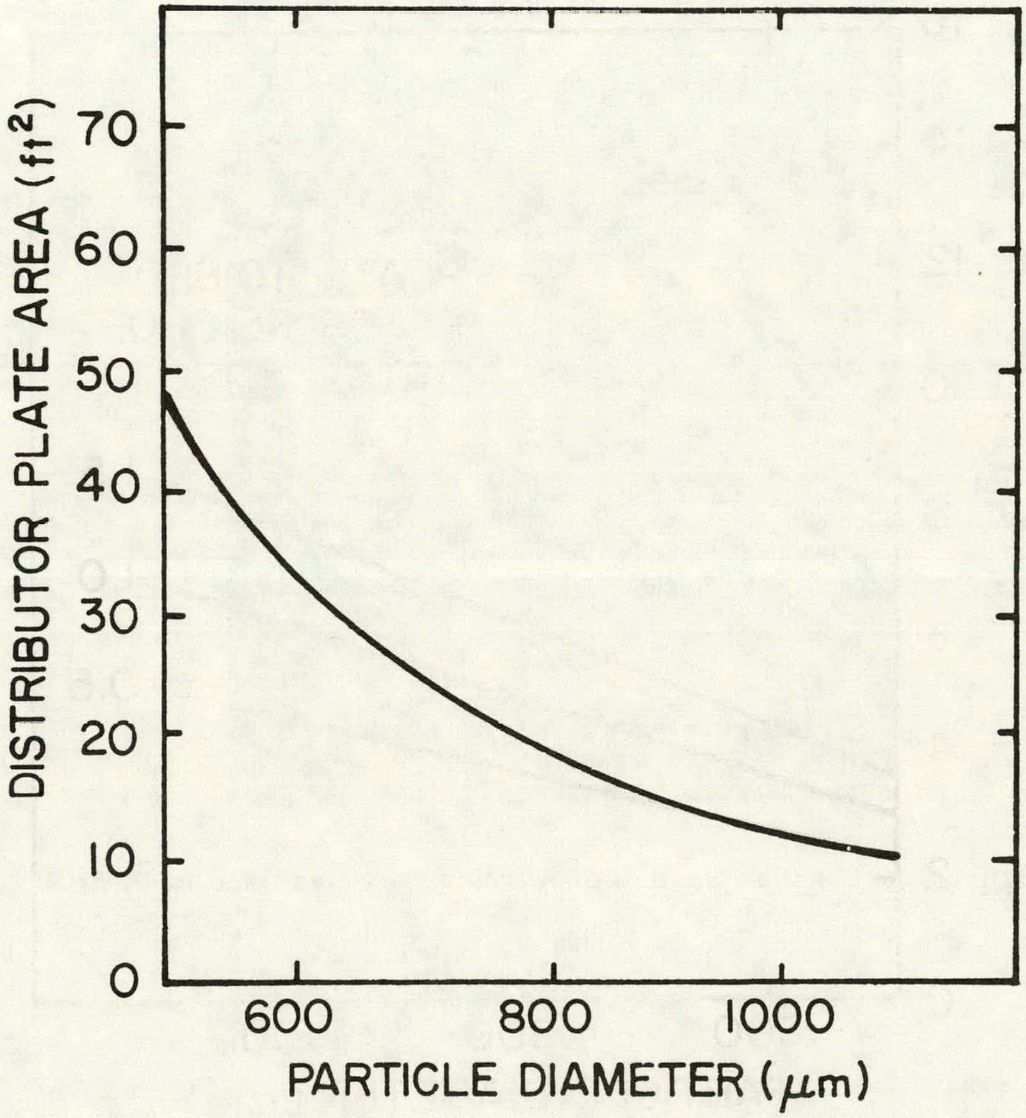


Figure 3.7 Distributor Plate Area vs Particle Diameter

Figure 3.8 Polished Section of Alumina Particles Used in FBWHR System

pellets such as those illustrated in Figure 3.9 can be used. The spherical alumina has fewer defects and, therefore, a diminished attrition potential.

3.4 RECUPERATOR ECONOMICS

With the fuel flow rate reduction determined from Section 3.1, the turndown determined from Section 3.2, and the size of the recuperator from Section 3.3, it is possible to determine the payback of the recuperator. Two situations are considered: a retrofit in which the furnace is already existing, and a new installation in which the recuperator is installed while the furnace is being built. The cost of retrofitting the recuperator is more expensive than a new installation because existing equipment has to be replaced and also because it is more difficult to install larger equipment in an existing facility.

The economics of each situation as applied to VMC's operation is shown in Table 3.2 using 1982 dollars. At 1000°F air preheat temperature and a fuel cost of $\$5/10^6$ Btu/hr, a yearly fuel savings, minus operational and maintenance costs, of $106,000 is realized. The total cost of building and installing the recuperator is $183,000 as a retrofit and $131,000 as a new installation. Hence, the payback is 1.7 and 1.2 years for the retrofit and new installation, respectively. This is considered an attractive payback by most users.

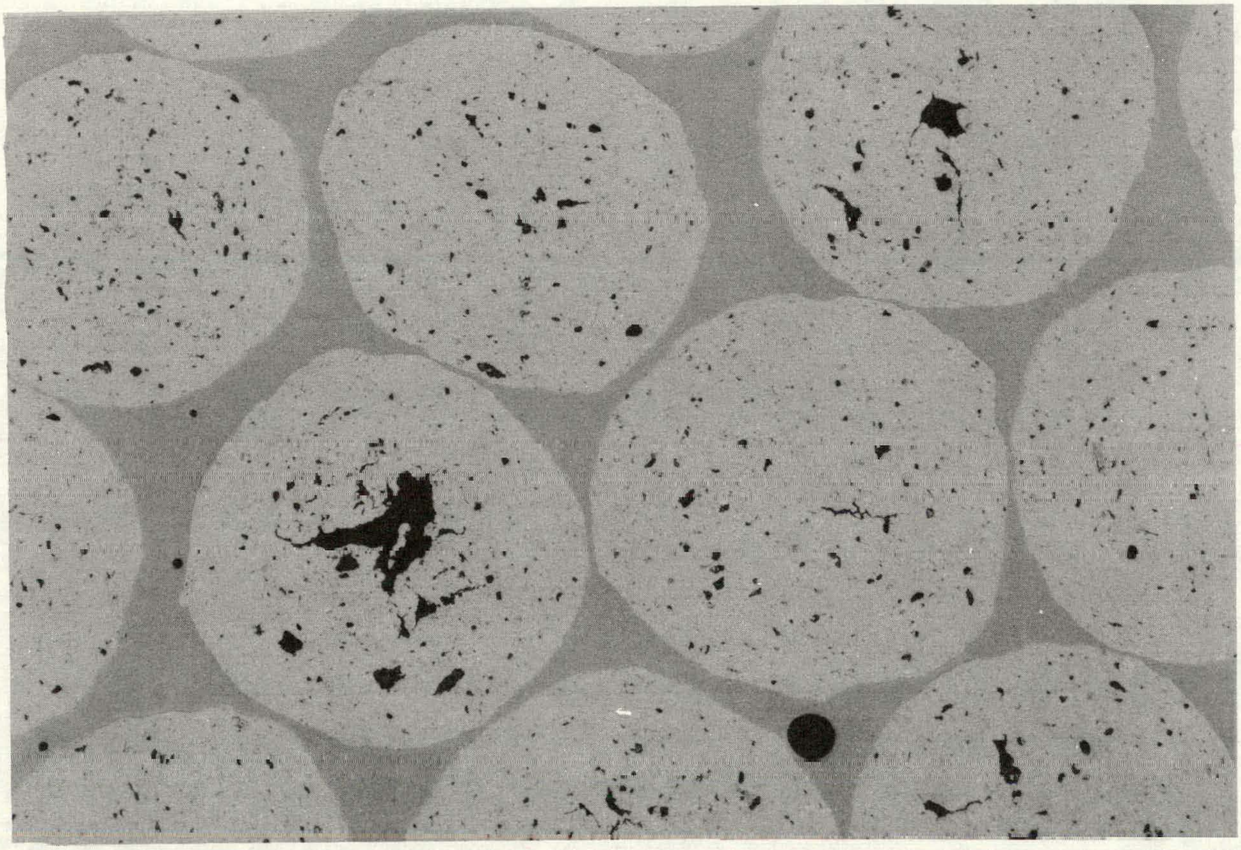


Figure 3.9 Polished Sections of Spherical Alumina Particles from Norton Company

TABLE 3.2

RECUPERATOR PAYBACK (AT 1000°F PREHEAT)

	Retrofit	New
Installed Cost	\$183,000	\$131,000
Yearly Fuel Savings	\$106,000	\$106,000
Payback (years)	1.7	1.2

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4. EQUIPMENT AND CONTROLS

This chapter deals with the equipment and controls selected for the full-scale demonstration unit at VMC. The combustion and exhaust system designs, including the actual design specifications, are discussed. The proposed methods of controlling furnace pressure and temperature are covered along with operational limits.

4.1 COMBUSTION SYSTEM

The existing combustion system is not capable of utilizing 1000°F preheated air. The burners are not rated for preheated air, and the combustion piping is too small to pass the lower-density combustion air. The present control system is also not suited for operation with a recuperator since it is not temperature compensated. For these reasons it is necessary to replace VMC's combustion system when the recuperator is installed. The design of the new combustion system described below was developed from information supplied by the North American Manufacturing Company with consultation from VMC.

4.1.1 Burners

The burners selected are the North American Magna Flame burners. These burners will have flame stability when using preheated air and will still be capable of supplying the same amount of energy as the existing burners when using ambient air. The burner blocks are not supplied by the North American Manufacturing Company but must be made on site. Because of the potential for high flame temperature, the proper selection of burner block materials is critical to successful operation. It should be noted that it has been assumed that the higher flame temperature will not damage the furnace refractory.

4.1.2 Combustion Air System

The proposed combustion air system is shown in Figure 4.1. The capacity of the blower is specified such that it can supply

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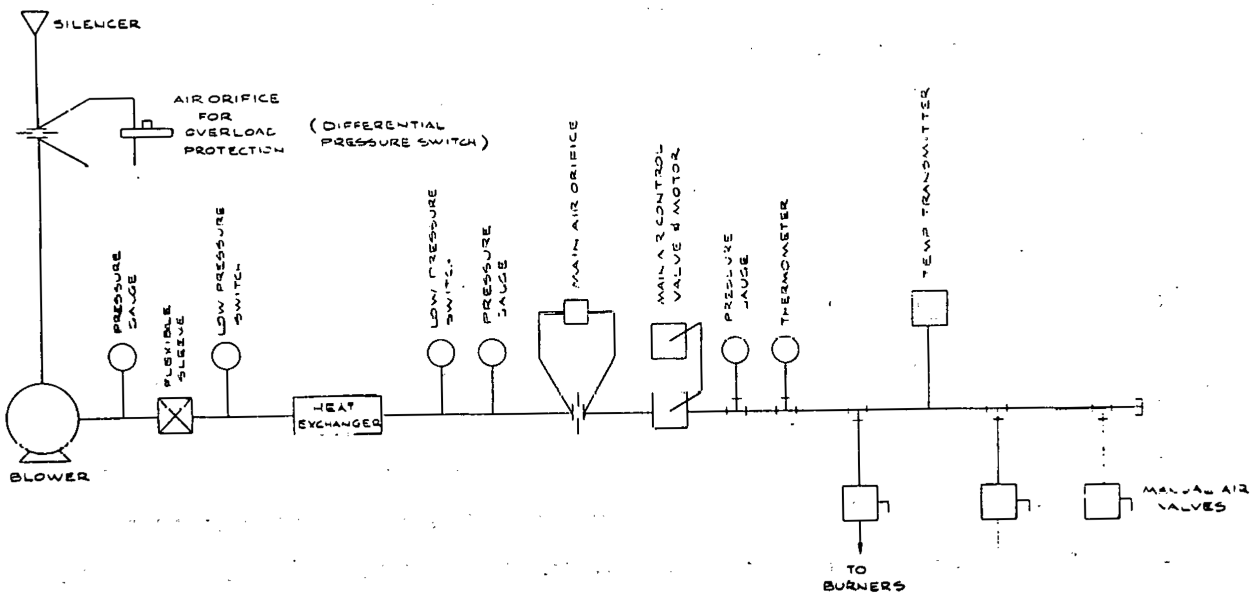

Figure 4.1 Air System

adequate ambient air to the burners at high fire. The specification for the blower pressure is dictated by the preheated air condition. This is because the air density decrease will result in a higher pressure drop in the system, even though the mass of the preheated air will be 30 percent less than that needed at ambient conditions.

There will be a number of protection devices on the system. One of the more significant overload protections on the blower will involve a differential pressure switch on an air orifice upstream of the blower. If there is a large increase in the flow rate due to a rupture in the heat exchanger, the blower will be protected. There will also be a pressure switch located downstream of the heat exchanger which will alert the operator if the heat exchanger is plugged. There will be a number of pressure and temperature gauges located throughout the system for easy monitoring.

4.1.3 Fuel System and Control

The firing rate of the burners is controlled by modulating the fuel flow. The fuel system is shown in Figure 4.2. The correct combustion air-fuel ratio will be monitored by a Marc Electronic air-fuel ratio control. Using signals from the main natural gas orifice and the preheated air temperature transmitter, the Marc control will regulate the main air control valve until it senses the correct reading across the main air orifice. This type of system will allow a constant air-fuel ratio over a wide range of operating conditions.

This combustion system includes all safety equipment including flame scanners, ignition transformers, pressure switches, vents, and safety shutoff valves. The flame supervision system will be mounted in a Nema 12 control panel.

4.2 EXHAUST SYSTEM

The system to exhaust the flue gases through the bed is complicated because hot, corrosive gases are being exhausted, and a pressure drop of

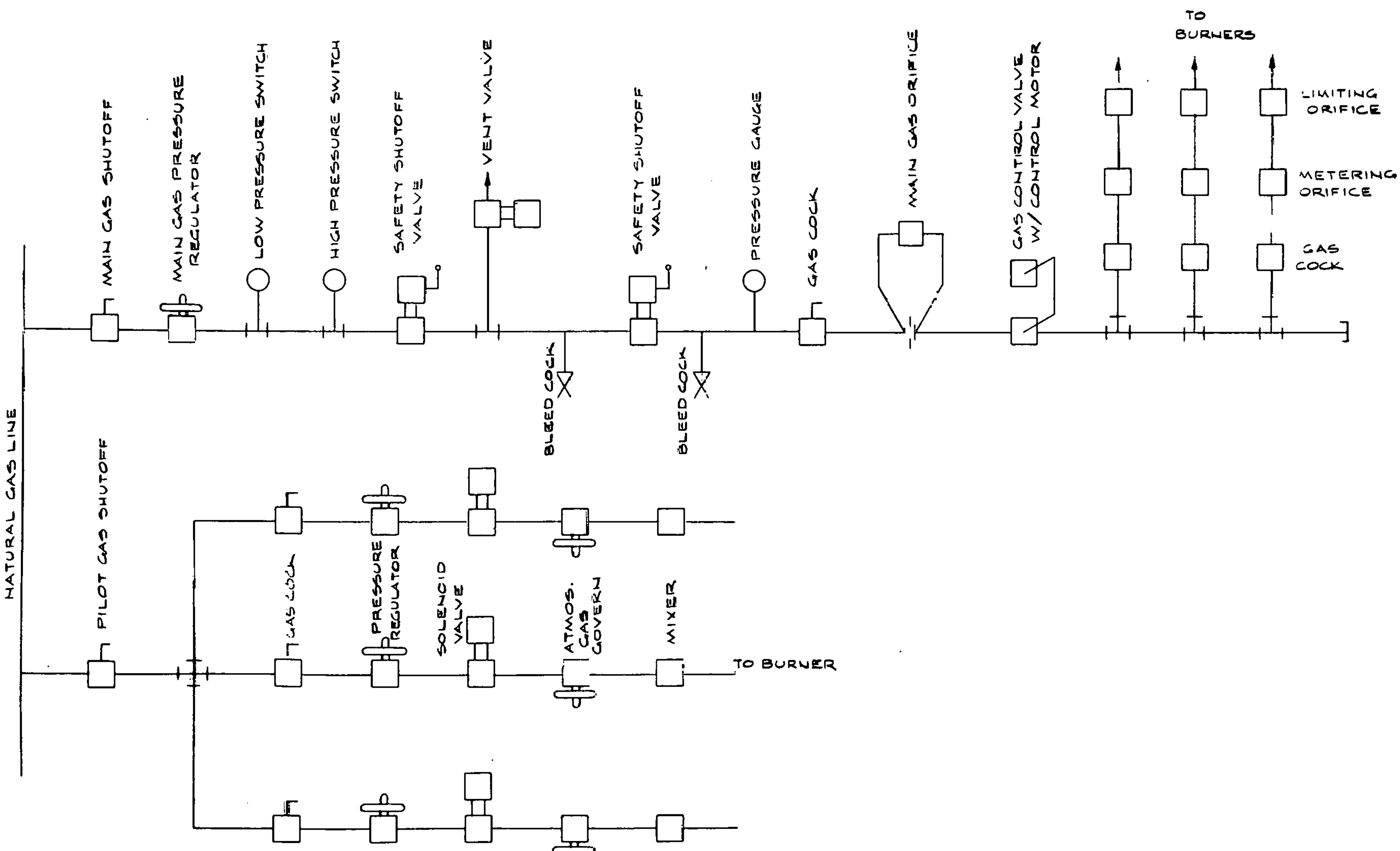

Figure 4.2 Fuel System

9½ in. is required (high fire). Also, the temperature of the gases leaving the bed is approximately 1200°F. Three alternatives were examined that could meet the above specifications - an exhaust blower, an exhaust blower with dilution air, and an ejector system.

A blower designed to operate at the above conditions is not standard equipment. The high temperature coupled with the high pressure dictate expensive materials and specialized construction. The blower that was most fully investigated used less than 30 hp at the design temperature. Unfortunately, potential reliability and maintenance are of great concern, and there are minimum temperature safety factors which have to be considered to prevent failure of the blower. Without resorting to water-cooled bearings there could be significant bearing problems. A special high-temperature damper will be needed to control furnace pressure. The cost of this option is close to $40,000.

An alternative option is to use ambient air to dilute the flue gas stream from 1200°F to 500°F after it has passed through the fluidized bed. With the new temperature specification and cold pressure rating, a blower can be selected that is of standard design and uses standard materials. A main damper located upstream of the blower can be used to control furnace pressure. The dilution air will be controlled by a damper operating off a temperature signal from the flue gas. This system has two disadvantages: a complicated control system is required, and there is a possibility of corrosion on the fin structure. The cost of this system is approximately $8000.

An alternative to an exhaust blower would be an ejector system. Using the venturi principle, a high-velocity stream of air will draw the waste gases from the flue and eject them out a stack. The total ejector height will be 25 feet and, along with the blower that supplies the high-velocity stream of air, will occupy a significant amount of space. Much of the ejector would be protruding through the roof and, thereby, would be subject to a wind load. Substantial quantities of steel would be needed to support such a configuration. This option would have a high power requirement, but corrosion would be minimal. The ejector would be supplied with a 125-hp motor. A low-temperature inlet damper on the blower would be used for furnace pressure control. This option would cost approximately $40,000.

The exhaust blower with dilution air will be used for the gas pumping system. There is a difference of over $10,000 per year in energy costs between this option and the ejector system, and this option is lower in capital cost by a factor of four. The high-temperature exhaust blower option is five times as expensive and is of questionable reliability.

4.3 CONTROL AND LIMITS

The control of the recuperator consists of a furnace pressure control, over-temperature protection, particle circulatory flow rate, and a gas sealing control. Figure 4.3 is a schematic of the control arrangement. The furnace pressure control system controls the flow through the recuperator and, hence, its pressure drop, and also controls the flow through the bypass. Over-temperature protection is used to limit the flue gas temperature entering and exiting the recuperator to avoid damaging the distributor plate and exhauster, respectively. Particle circulatory system control is used to set and maintain the particle flow rate and particle dipleg inventory for gas sealing. Control of the burners and combustion blower are part of the combustion system and are discussed previously in this report.

At the present time, the furnace pressure is controlled by a jet damper on a natural-draft stack. For the new configuration, a dual system will be used which will incorporate both the existing jet damper in a bypass arrangement plus the new damper on the new exhauster.

At low fire the fluidized beds will be stagnant, although the flue gases will pass through the upper bed. The dilution damper upstream of the blower will proportionally control the temperature of the gases to

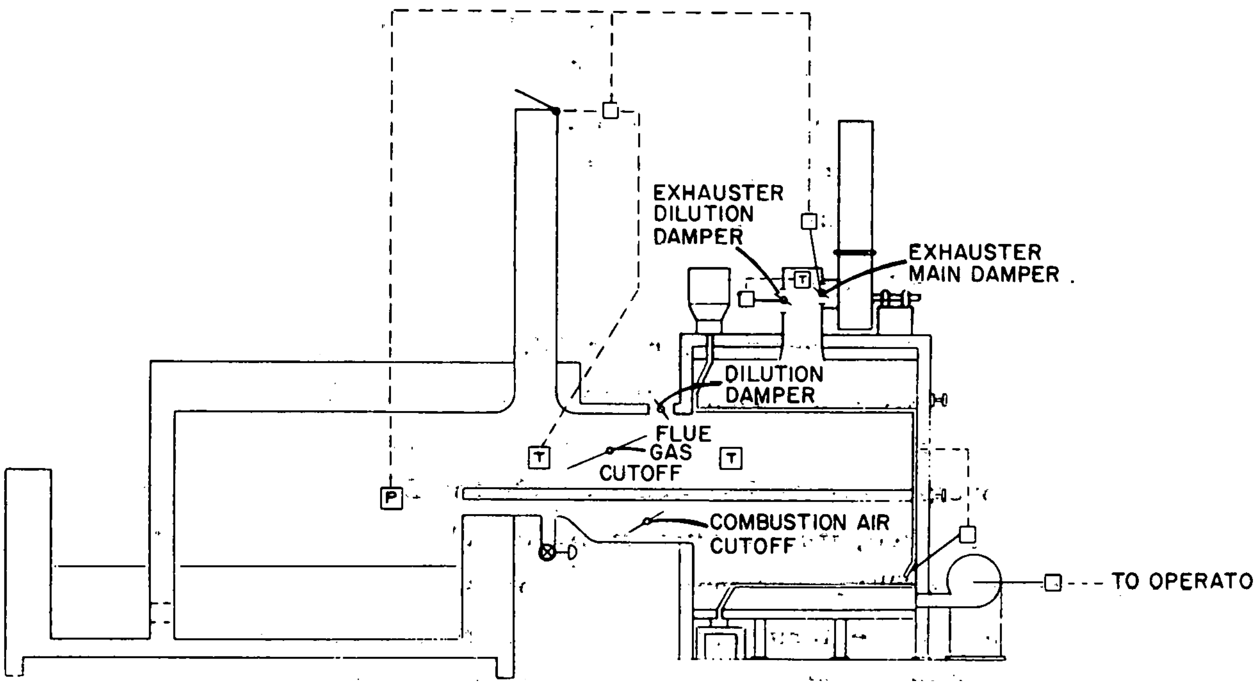

Figure 4.3 Schematic of Control Strategy

the blower at 500°F. The combustion air system will also continue to flow air through the lower fluidized bed but, as in the upper bed, there will be no material flow.

The main damper just upstream of the exhaust blower will be used for controlling the furnace pressure. The bypass jet damper will be fully activated at low fire, thereby preventing the flue gases from escaping up the auxiliary stack.

As the firing rate of the burners increases, the main damper will open upon receiving a signal from the furnace pressure controller. When the maximum recuperator design flow is reached, the damper will hit a preset limit switch. Furnace pressure will then be controlled by the jet damper on the bypass stack which will allow the excess gases to bypass the fluidized bed.

This system has temperature limits on various components that could be exceeded if safeguards were not supplied. For example, if the upper bed were to become defluidized, the temperature of the gases leaving the bed would be much higher than normal, which could possibly damage the exhauster. If the temperature at any point in the system is above a pre determined limit, then a dilution damper will be activated to cool the gases.

5. FOULING AND MATERIALS TESTING

There are currently two major problems of concern involving the design of the FBWHR system - upper distributor plate fouling, and materials selection. Several small-scale field tests were conducted to determine the extent of each of these problems. In this chapter the bases of the concerns are discussed and results of the tests conducted are presented.

5.1 UPPER DISTRIBUTOR PLATE FOULING

One concern with the FBWHR system is the possible deposition (or condensing) of particulate matter on the hot distributor plate. This material builds up around the plate holes, increasing the pressure loss and reducing the gas flow rate. The effect is shown in Figure 5.1. The recuperator flow rate through the distributor plate is plotted against the hole diameter. The nominal distributor plate hole diameter is 0.063 in. At the maximum blower pressure, the flow rate is 3.3 lbm/sec with the holes open. As the holes plug, the total open area is decreased. Since the exhaust is pressure-limited, the flow rate through the holes is reduced (solid line). Fouling has a reduced effect during turndown (dashed line) since the exhauster is no longer pressure-limited. Here, it is possible to maintain flow, up to a reduction in hole diameter of 30 percent. Reduction in the flow rate at high fire reduces the recuperator effectiveness and, hence, combustion air preheat temperature, as shown in Figure 5.2. A 20 percent blockage of the open area would result in a preheat temperature reduction of over 100°F.

Two on-site experiments were conducted in this program to investigate the susceptibility of the distributor plate to fouling: one internal, and one external, to the flue. These are shown in Figure 5.3. The internal fouling experiment consisted of a $1\frac{1}{2}$ in. diameter Incoloy 800 distributor plate, 1/16-in. thick, with 1/16 in. diameter holes (7 percent open area). The plate was held in an alumina holder open at the upstream

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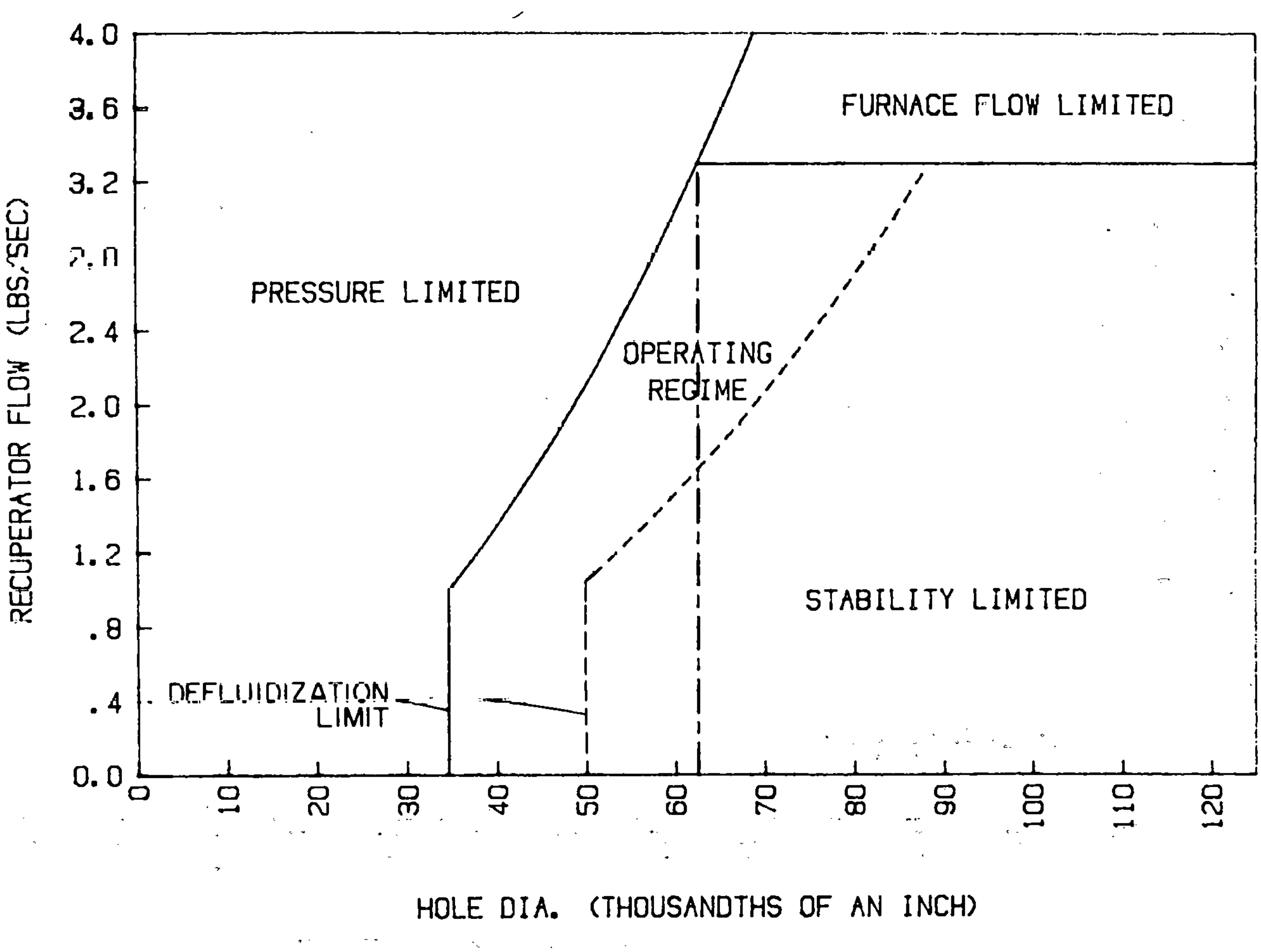

Figure 5.1 Reduction in Recuperator Gas Flow Due to Distributor Plate Fouling

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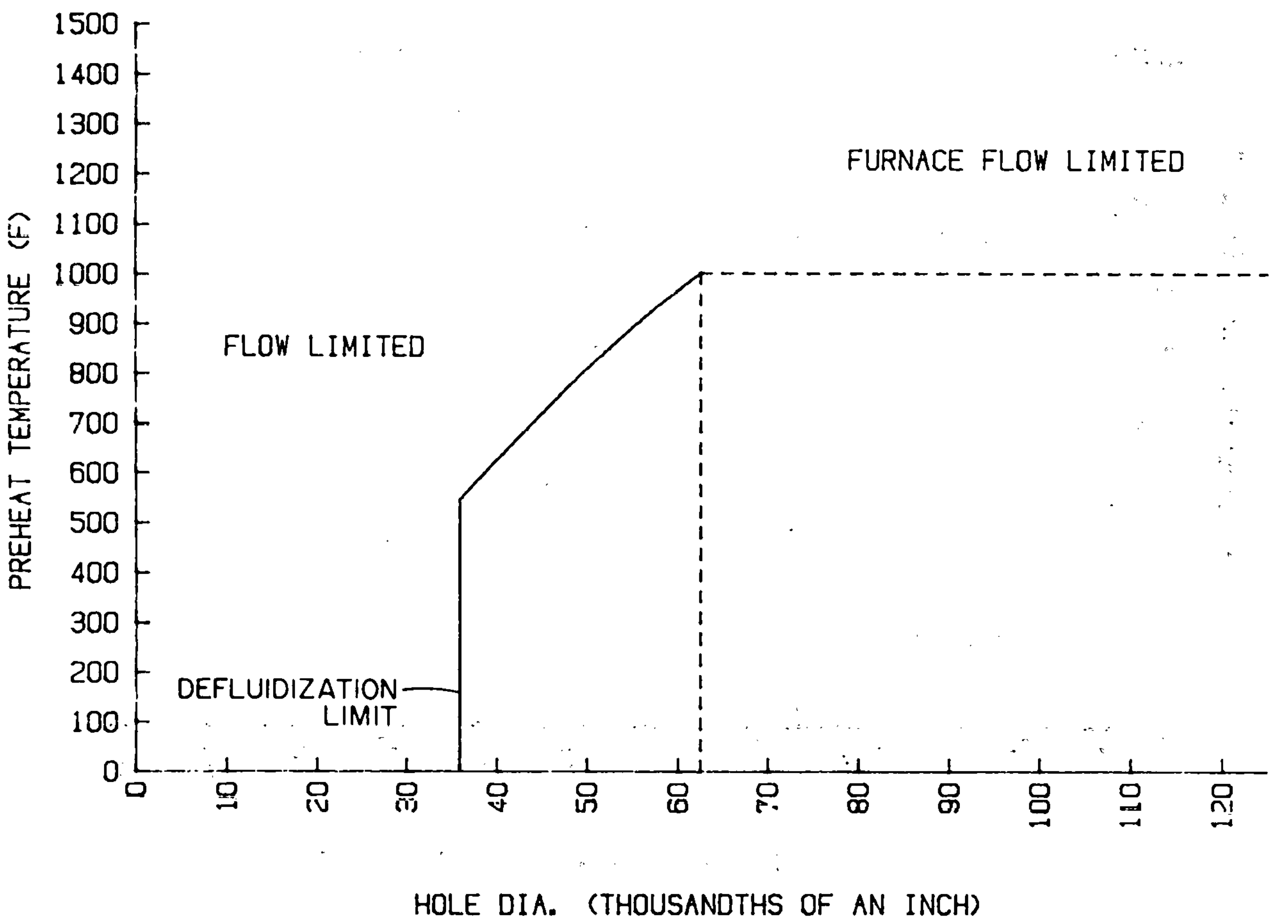

Figure 5.2 Reduction in Combustion Air Preheat Temperature Due to Distributor Plate Fouling

89-682

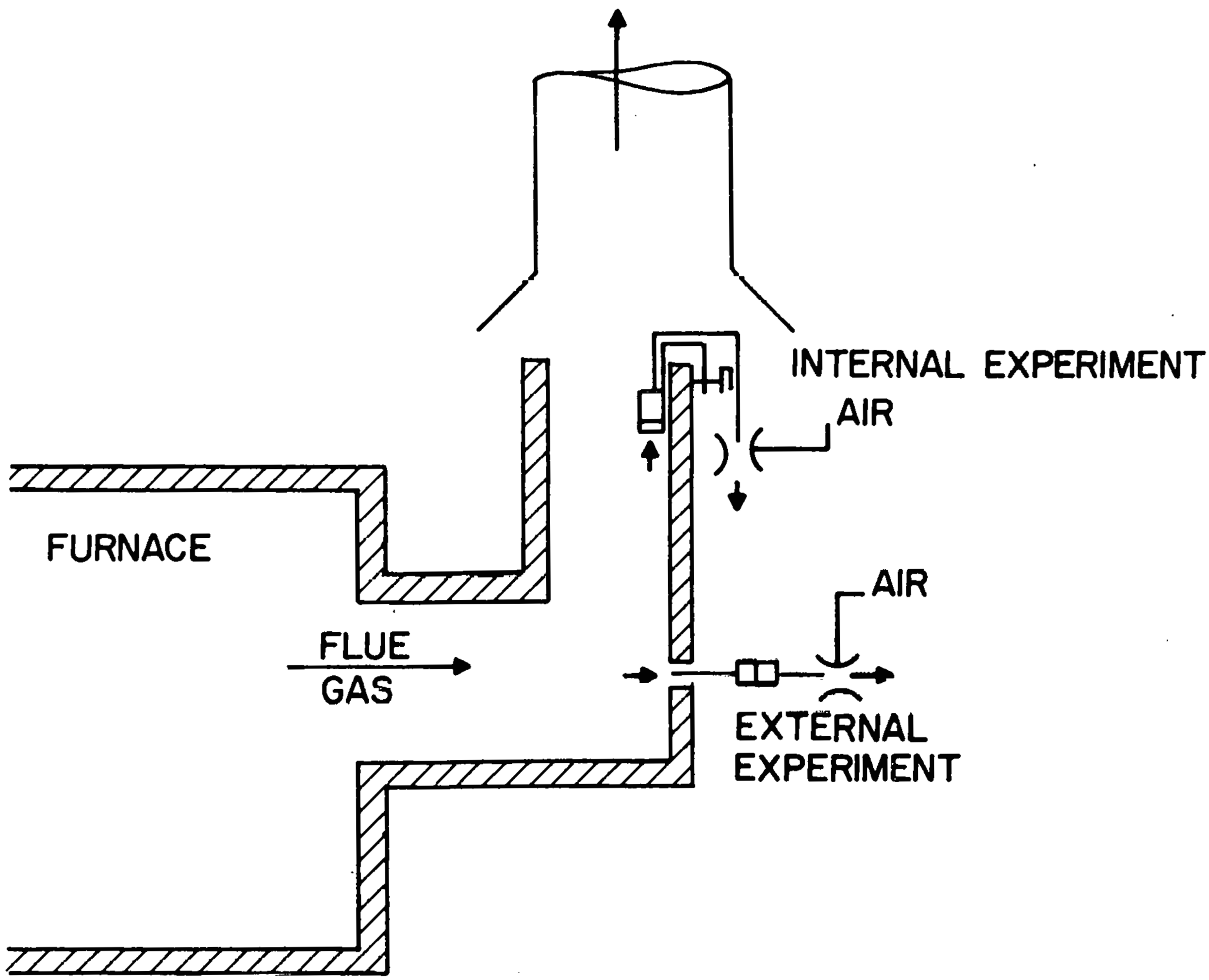

Figure 5.3 Fouling Experiment Locations

end. The downstream end was connected to a jet pump which pulled the flue gases through the plate. The plate and holder were immersed in the furnace flue as shown in Figure 5.4.

The external experiment, shown in Figure 5.5, used a distributor plate similar to the one in the internal experiment. The holder, however, was made of stainless steel. A jet pump, located immediately downstream of the plate, drew flue gases through a 1 in. diameter hole in the flue wall and then through the distributor plate. The temperature of the flue gas for the external experiment was considerably reduced at the distributor plate because of the relatively small flow rate and larger holder surface area. This was not true for the internal experiment.

The internal fouling test was inspected after 360 hours of continuous operation. The flue gas environment was typical during that time. Figures 5.6 and 5.7 show the flue gas temperature and total burner air flow rate, respectively. The temperature is cycled to over 2200°F.

An immediate inspection showed 14 of 41 holes to be completely blocked with a loose, brown, granular deposit. Sixteen holes were partially blocked. This resulted in a 50 percent reduction in open area - a serious fouling problem. Figure 5.8 shows a photomicrograph of a partially blocked hole. The fouling deposit was observed to be loose and easily dislodged.

A chemical analysis of the deposit, distributor plate, and plate holder was undertaken to determine the source of the deposit. The results are shown in Table 5.1. The major constituents of the deposit are calcium, zinc, nickel, and iron. Both the calcium and zinc, accounting for 42.1 percent of the deposit, cannot be traced to the plate or holder and therefore must come from the furnace. Zinc is a common alloying element and calcium can be found in the salt added to the melt and in the aluminum scrap.

The second fouling experiment, external to the flue, was inspected after 200 hours of operation and showed no fouling. A later check after

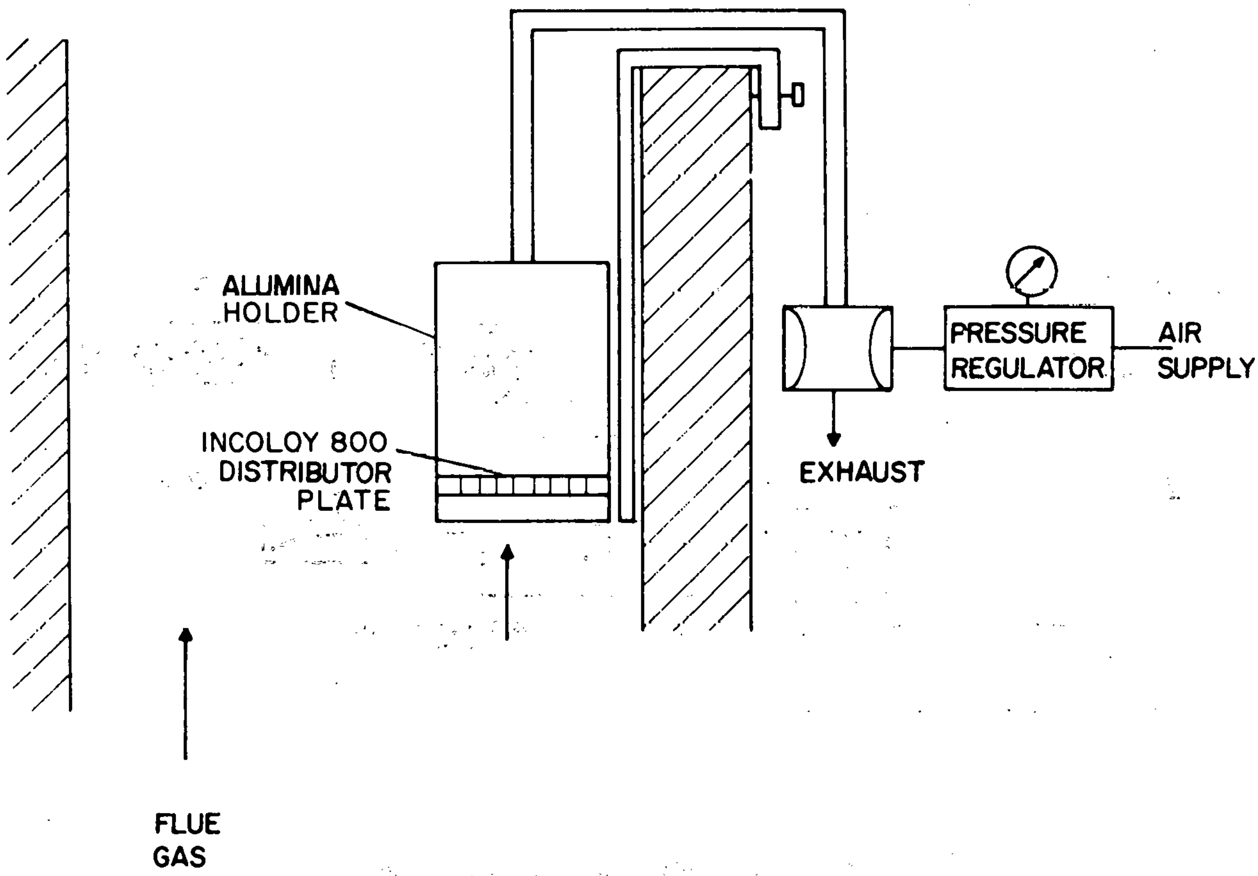

Figure 5.4 Internal Fouling Experiment

99-682

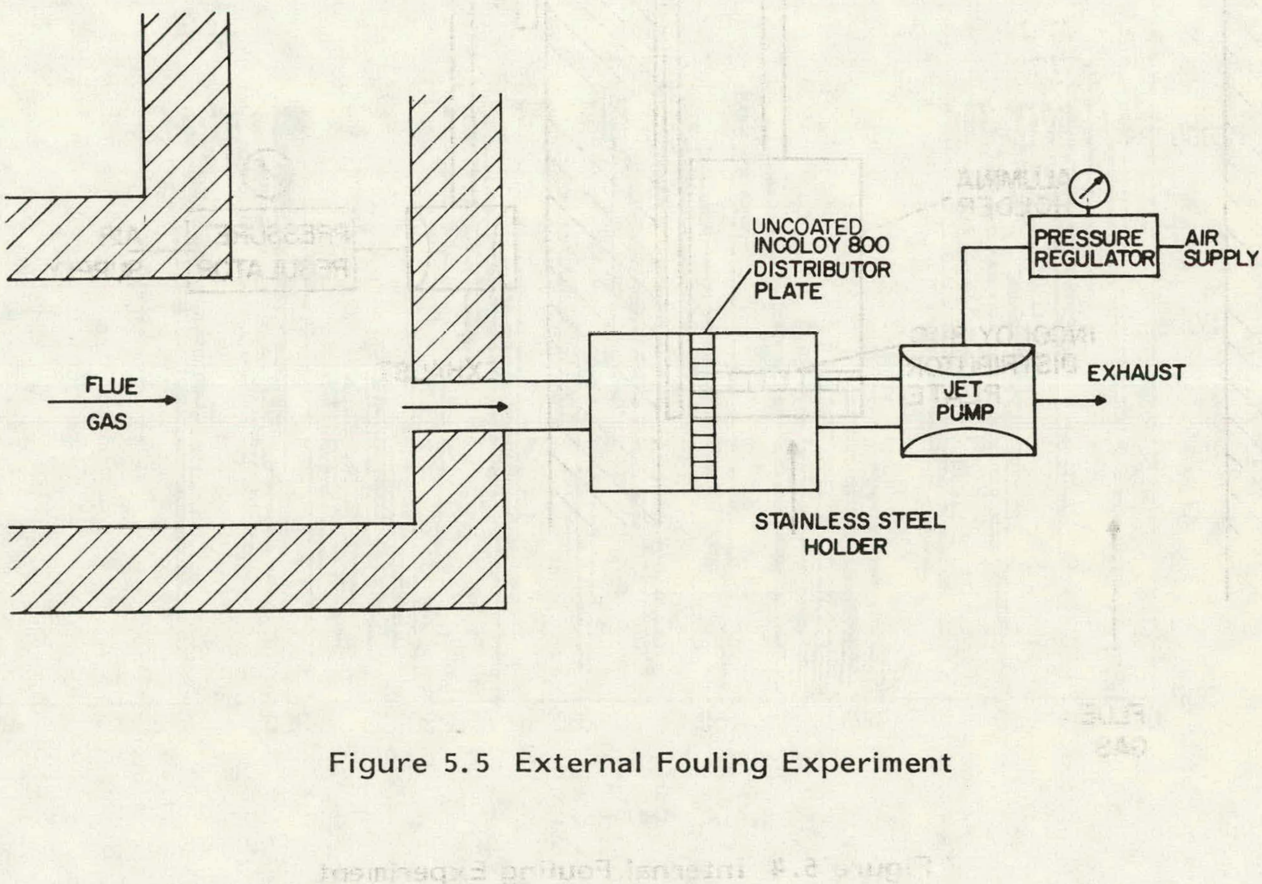

Figure 5.5 External Fouling Experiment

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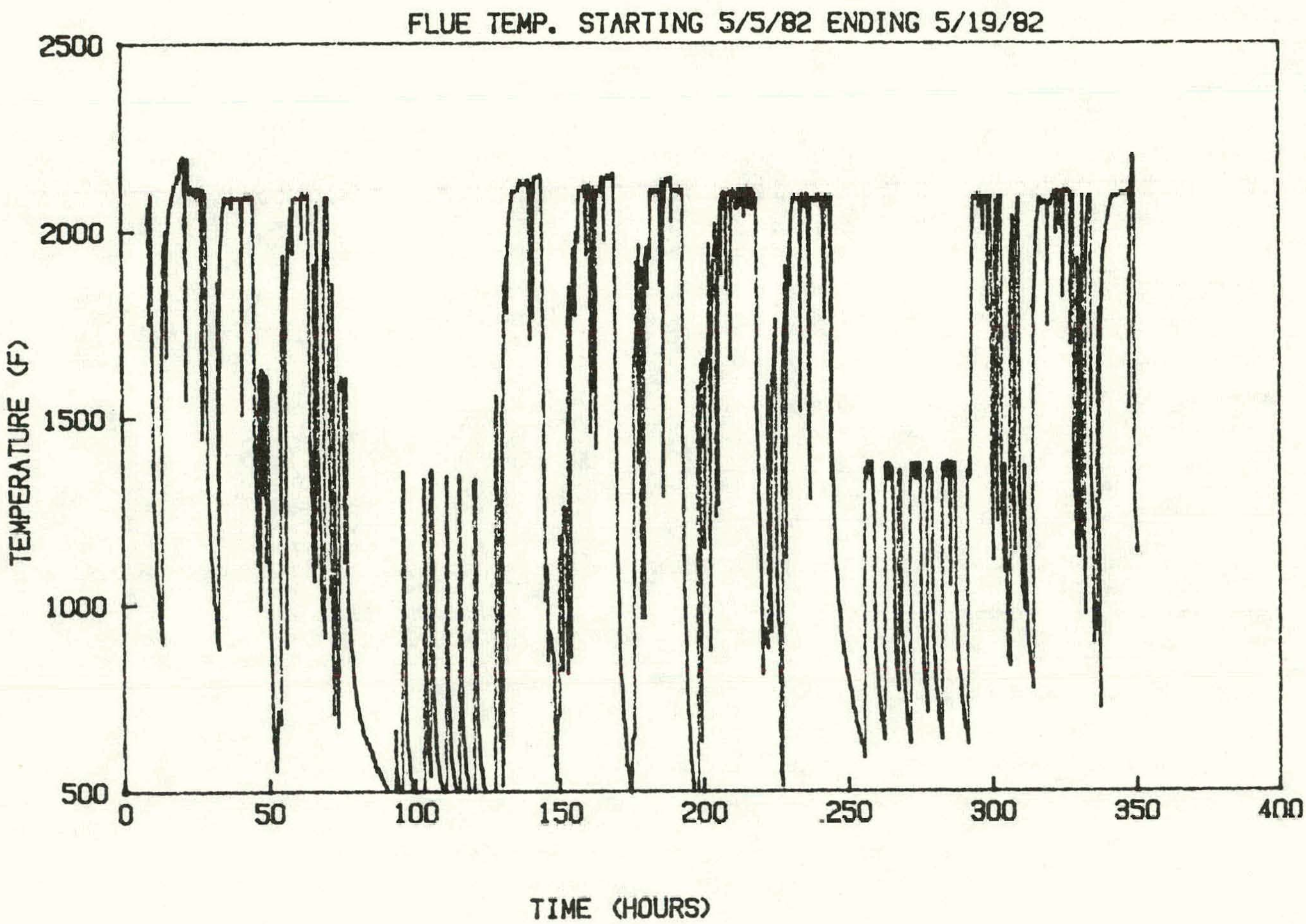

Figure 5.6 Flue Gas Temperature While the Internal Fouling Test Was Operating

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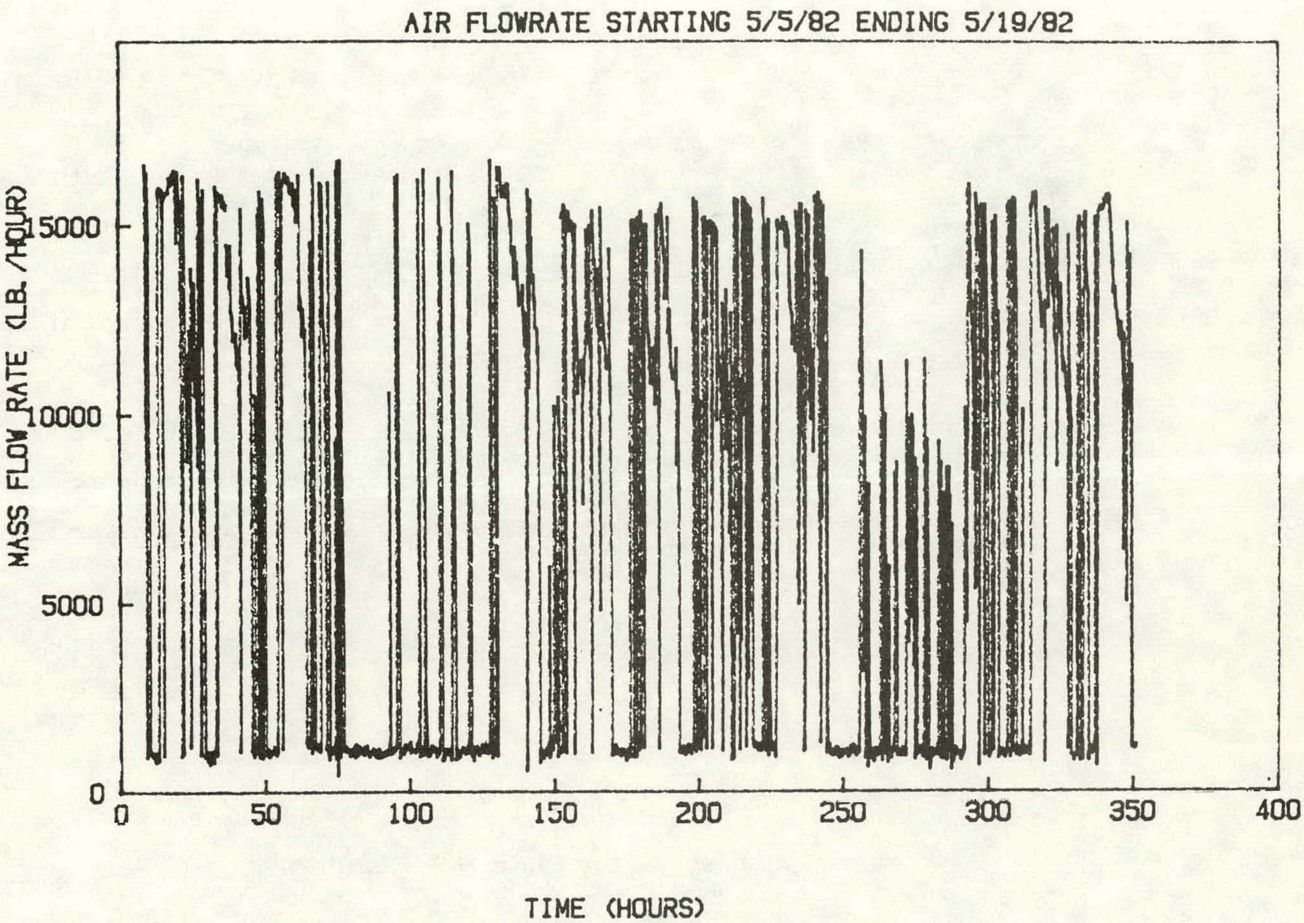

Figure 5.7 Total Burner Air Flow While the Internal Fouling Test Was Operating

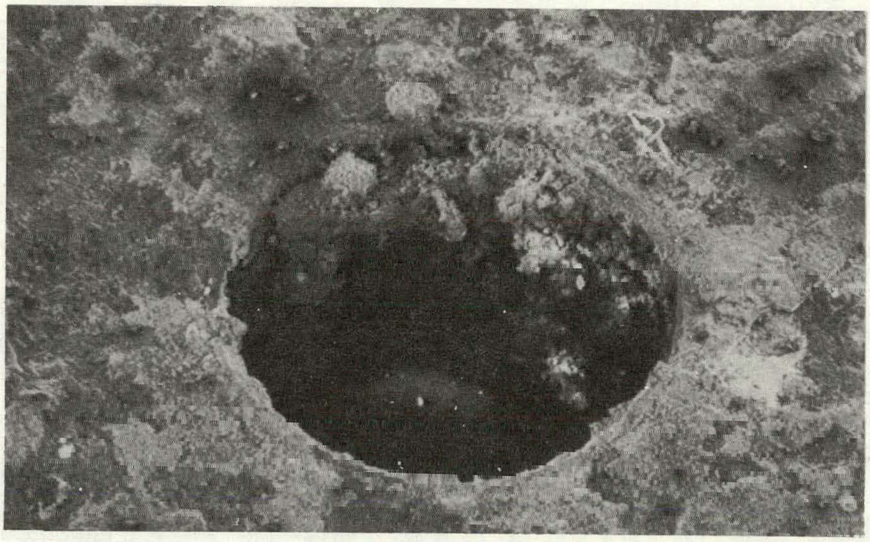

Figure 5. 8 Distributor Plate Hole Fouling

over 1000 hours of operation showed an amorphous buildup on both the upstream and downstream sides of the distributor plate. The buildup appeared smooth and had a greenish-brown color. The analysis of this material is also shown in Table 5.1. The deposit consisted primarily of iron, chlorine, and chromium. The chlorine is present in the flue gases while the iron and chromium are present in the Incoloy plate. Thus, it appears that the deposit resulted from chlorine attack of either the holder or the plate. This may or may not be a problem at the higher temperatures encountered in the FBWHR system.

These two experiments have not shown conclusively the susceptibility of the FBWHR system to fouling. Rather, they have shown the susceptibility of uncoated metals to chlorine attack at low temperature and that material can be captured by the plate at higher temperatures. However, the rate, or even the seriousness of this capture has not been identified. Thus, further tests are required.

5.2 UPPER DISTRIBUTOR PLATE MATERIALS TESTING

The requirements of the distributor plate material are that it:

- be resistant to the corrosive agents in the flue gases
- retain strength at high temperature
- remain relatively flat after fabrication
- be capable of being fabricated with 1/16-in. holes spaced on 1/4-in. centers
- be readily available in sizes up to 20 ft^2
- be reasonable in cost
- be maintenance free for periods of one year or more

Two materials have been identified as potentially meeting these criteria: aluminum-diffusion-coated inconel, and silicon carbide. Bare metals were eliminated because of a lack of corrosion resistance. Alumina, an

TABLE 5.1

DEPOSIT ANALYSIS (percent by weight)

	External Fouling Experiment	Internal Fouling Experiment	Incoloy 800	Alumina Holder	316 SS
Calcium	-	19.7	-	-	-
Zinc	Trace	22.4	-	-	-
Nickel	7	21.9	32.5	-	10-14
Iron	44	15.8	46.0	1	Balance
Chlorine	38	-	-	-	-
Chromium	10	8.6	21.0	-	16-18
Potassium	-	-	-	-	-
Sodium	-	-	-	-	-
Silicon	-	2.6	0.5	7	1
Aluminum	Trace	1.9	0.4	92	-
Magnesium	-	1.5	0.8	-	-
Copper	Trace	-	0.4	-	7

excellent corrosion-resistant material, was eliminated because of its poor thermal shock resistance. All other ceramics were also eliminated because of either their poor thermal shock resistance, poor corrosion resistance, or poor fabricability.

The coated Inconel plate is currently considered to be the best. The coating consists of aluminum, diffused about 5 mils into the base metal. Upon exposure to the flue gases, the coating forms an alumina layer which is highly corrosive-resistant and protects the base metal. This material is particularly applicable to the FBWHR system because it is easy to fabricate, can be obtained in one piece, and is relatively inexpensive ($3000). However, the material is being operated at the upper limit of its temperature range which raises concerns about its stress rupture life and warping.

To see how well this material would survive in the flue gas environment, a one-square-foot piece of aluminum-diffusion-coated* perforated Inconel 625 was inserted in VMC's No. 2 furnace. Flue gas temperature for the first 911 hours is given in Figures 5.6, 5.9, and 5.10. Temperatures were as high as 2200°F during this test, with over half the time at temperatures in excess of 2000°F. After 911 hours of exposure a small piece of the plate was removed and photomicrographs taken. The photomicrographs of the exposed sample are shown in Figure 5.11. For comparison, a photomicrograph of an unexposed sample is shown in Figure 5.12. The top micrograph of Figure 5.11 shows that approximately 50 percent of the coating depth is damaged. The middle and lower photomicrographs show that approximately 30 percent and 20 percent, respectively, of the coating depths are damaged.

The life of the coating can be estimated by the following procedure:

1. Coating life is defined as the point at which the oxidation attack completely depletes the coating.

*The coating was applied by Coatings Technology Corporation, Branford, Connecticut.

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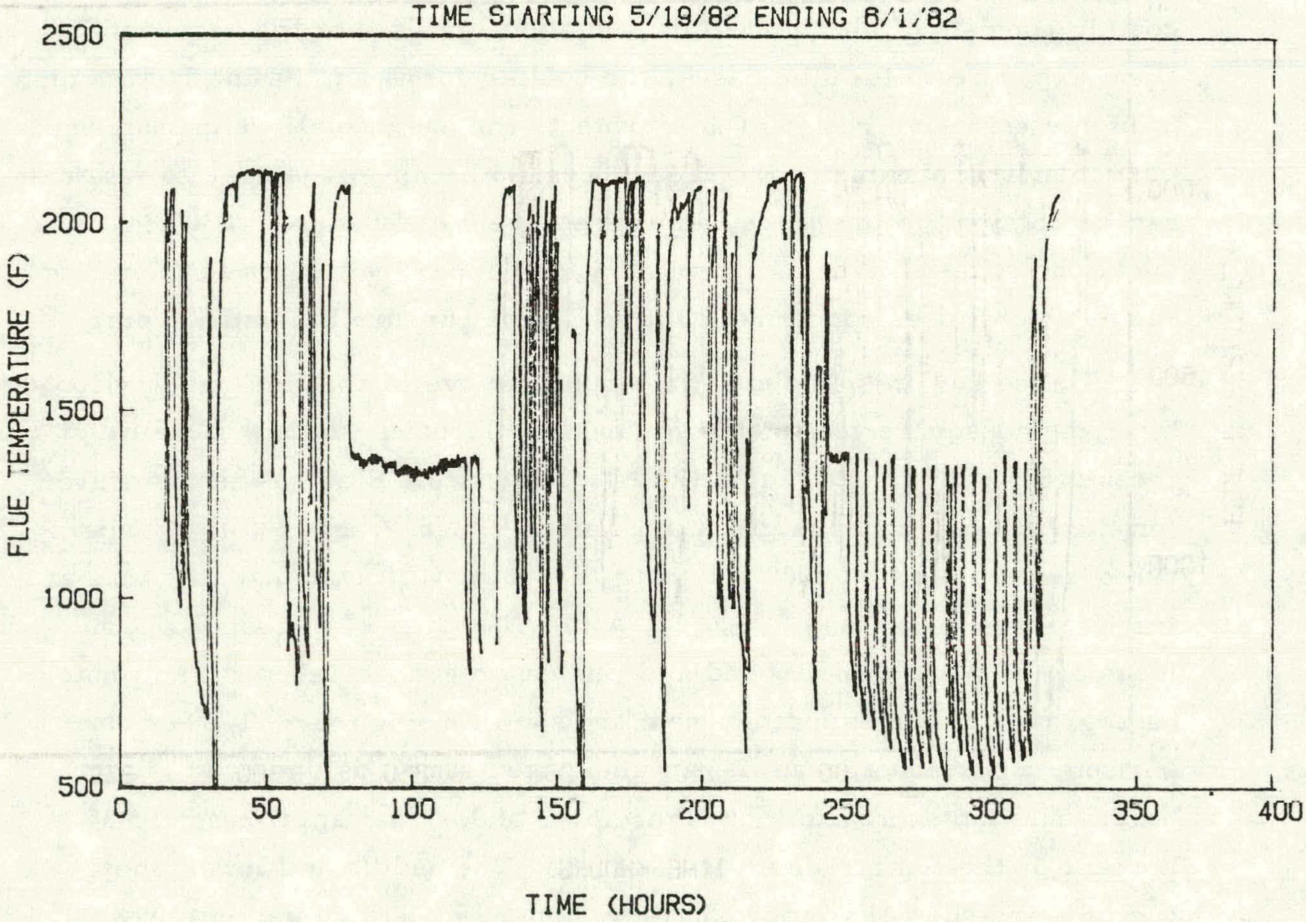

Figure 5.9 Flue Gas Temperature During the Materials Exposure Testing

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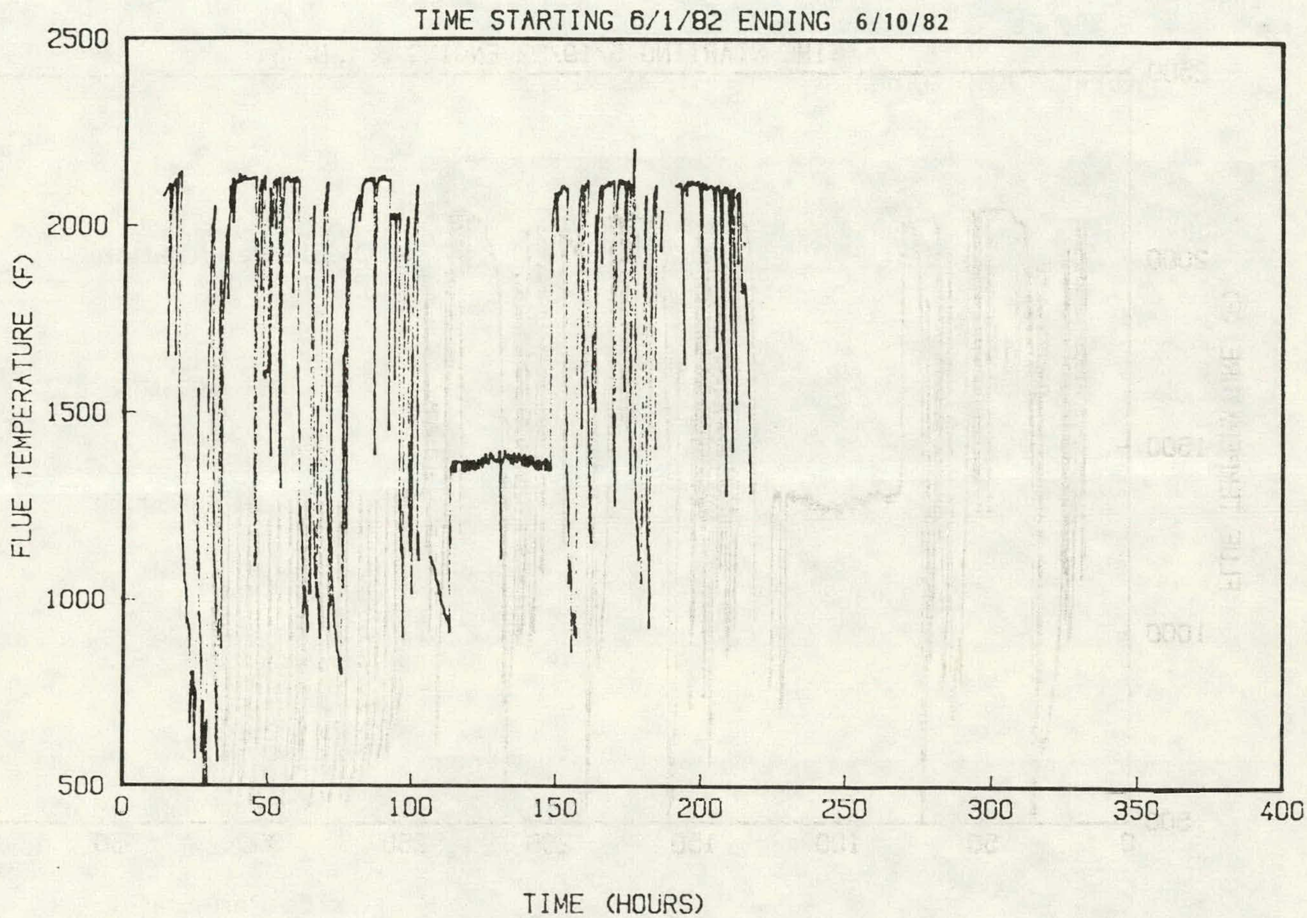
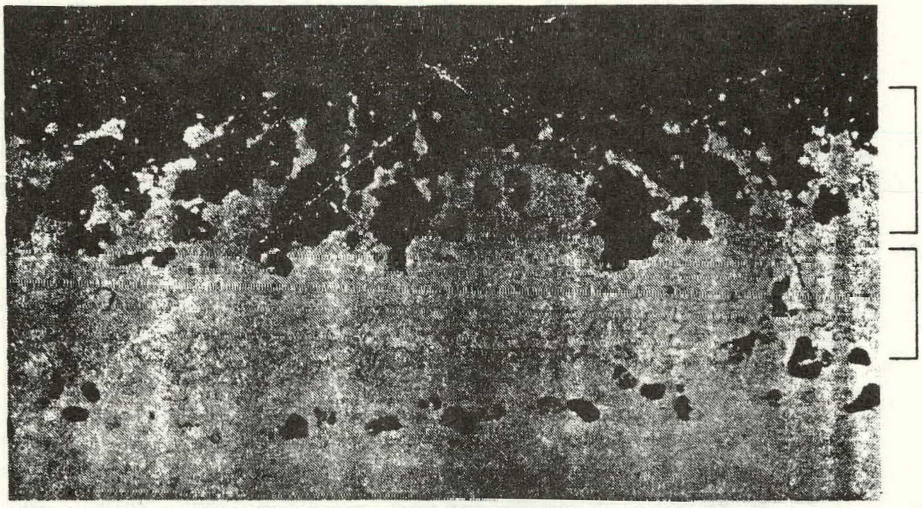
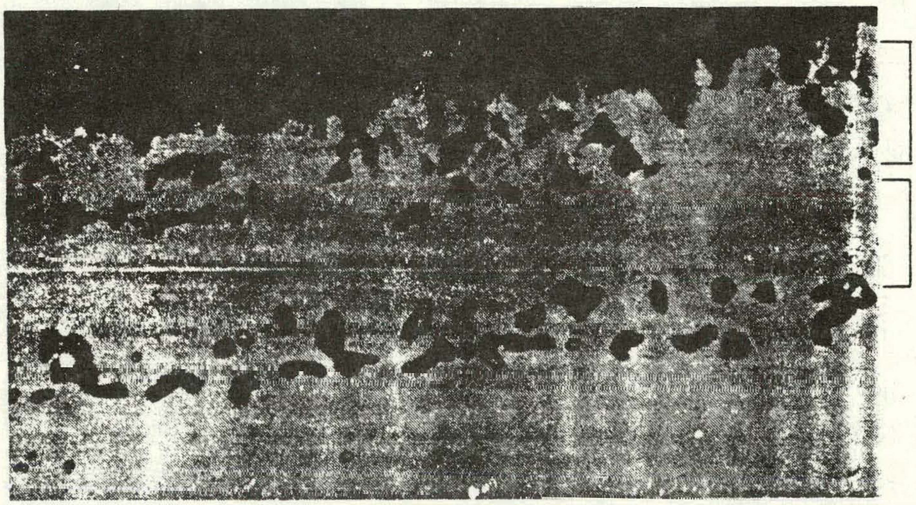


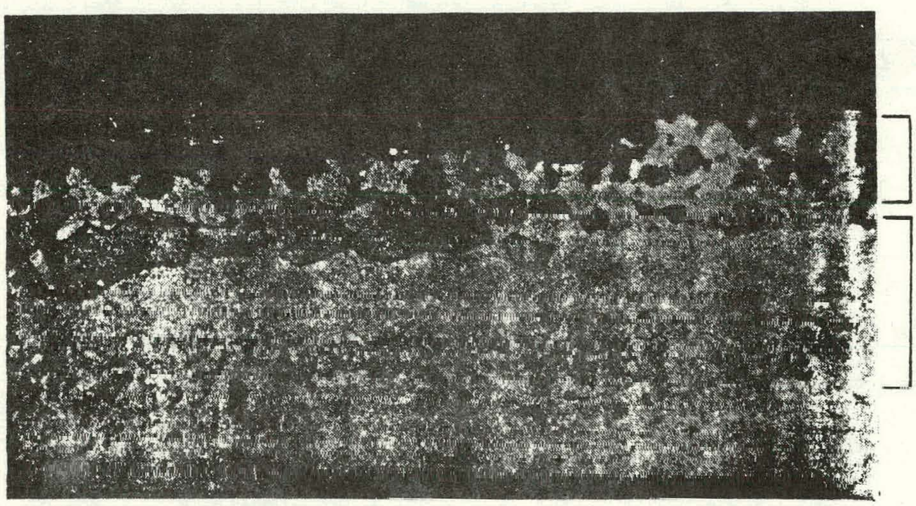
Figure 5.10 Flue Gas Temperature During the Materials Exposure Testing



Worst: Approximately 50% Life Used



Average: Approximately 30% Life Used



Best: Approximately 20% Life Used

Figure 5.11 Photomicrographs of Exposed Coated Inconel

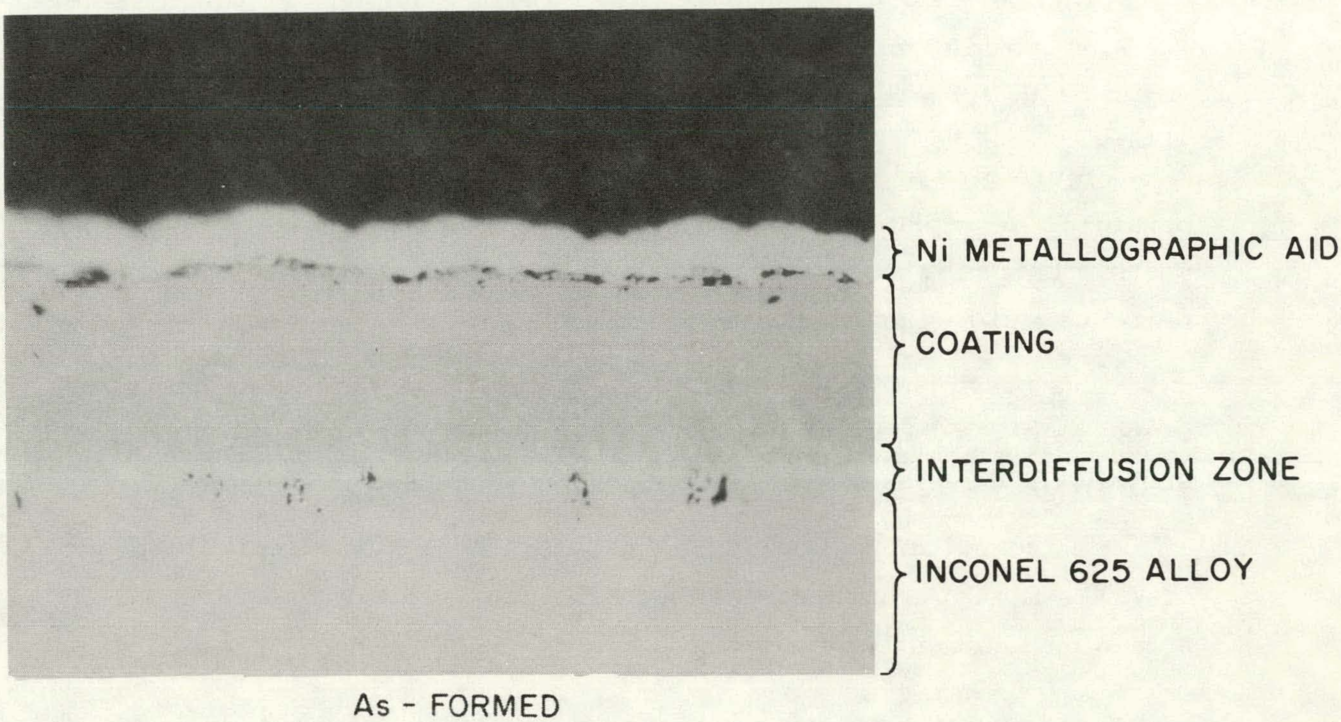


Figure 5.12 Photomicrograph of Unexposed Coated Inconel

2. The rate of damage to the coating at a given temperature is assumed to be linear (i.e., an observed coating depletion of 50 percent in 911 hours would imply the coating life to be 1822 hours).

3. The life of the coating can be corrected for temperature effects. A reduction in plate temperature of 100°F yields an increase in life by a factor of 2-1/2.

Figure 5.13 shows that the life of the coating is a function of temperature. At a plate temperature of 1900°F, the coating life is about two years. This fully meets all design criteria. However, results are still tentative and further testing is required.

It is possible to operate the plate at 1900°F while the flue gases are in excess of 2000°F by proper design of the shell insulation or by diluting, slightly, the flue gases with ambient air, as discussed in Section 4.3.

The coated Inconel was again inspected after 2250 hours of exposure in VMC's flue. An inspection showed the plate to have no visible damage and to be functionally unaffected.

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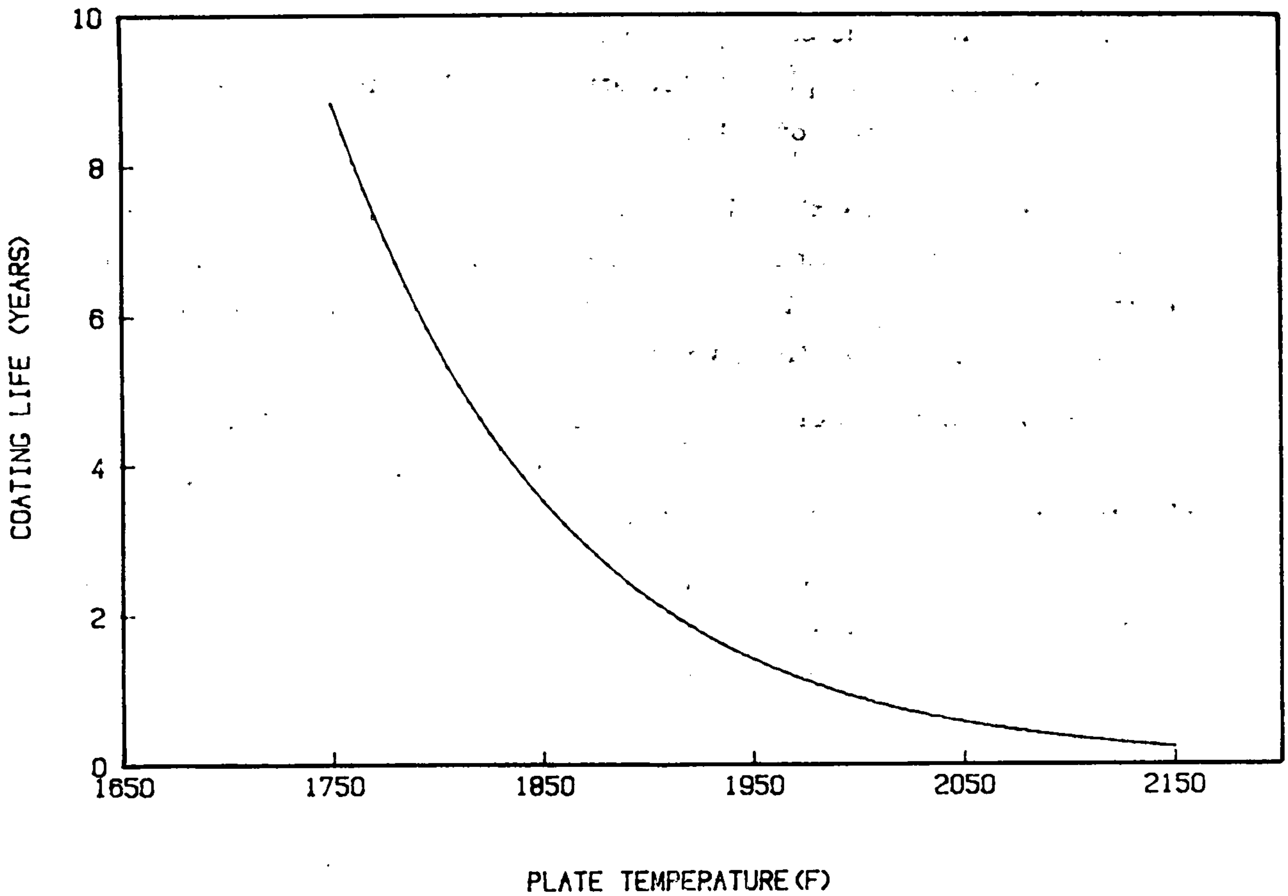

Figure 5.13 Effect of Temperature on Coating Life

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6. CONCLUSIONS

Work to date has shown that the Fluidized Bed Waste Heat Recovery System is a viable concept. The need it fulfills is for waste-heat recovery from high-temperature, dirty and corrosive furnace exhaust gases. The lack of reliable equipment results in furnace exhaust temperatures frequently exceeding 2000°F, and payback periods for these applications can be as short as 1-1/2 years. However, the technology to build the FBWHR system does not exist. Fluidized bed technology is mature, and the technology base necessary to develop the two beds existed prior to this program. In this program, the specific design parameters have been developed. However, deficiencies in the technology base still exist in the areas of high-temperature materials, heat exchanger fouling, and system integration. This program will resolve these deficiencies.