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FLUIDIZED-BED WASTE-HEAT RECOVERY SYSTEM DEVELOPMENT

Semiannual Report for August 1, 1981—January 31, 1982

By
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**FLUIDIZED-BED
WASTE-HEAT RECOVERY
SYSTEM DEVELOPMENT**

**SEMIANNUAL REPORT
1 AUGUST 1981 THROUGH 31 JANUARY 1982**

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EXECUTIVE SUMMARY

A major energy loss in industry is the heat content of the flue gases from industrial processes. One effective way to utilize this energy from hot flue gases, which is applicable to all processes, is to use it to preheat the combustion air. 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 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 preceding six-month period are described. Specific accomplishments 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 conclusion, the FBWHR system fulfills a real need: waste-heat recovery from high-temperature, dirty and corrosive furnace exhaust gases. Efforts to develop a technology needed to build this system are continuing.

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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 fuel 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 (Gerstner and Stake, 1977), 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. The savings would be even greater for a higher effectiveness recuperator.

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 Recuperator Effectiveness with Furnace Exit Temperature, T_1 , as Parameter (Natural Gas, 10% Excess Air)

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. The need, then, 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

Figure 1.4 Fluidized-Bed Air Preheat System

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 such aluminum plants in the United States (The Aluminum Association, 1976). Output from these plants was 1,371,000 tons in 1976. This was 27 percent of domestic aluminum consumption of 5,118,000 tons (Starper and Kurtz, 1975).

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 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.

During this reporting period, work proceeded on finalizing the parameters needed to design the FBWHR system. Specifically:

- Work was initiated to characterize the furnace operation and environment;
- The fluidized-bed performance was characterized;
- The particle circulation system was developed;
- The distributor plate specifications were defined, and materials of construction investigated; and,
- A systems analysis was completed.

This work is described in the report.

2. HOST SITE CHARACTERIZATION

2.1 HOST SITE DESCRIPTION

VMC is the host company for the FBWHR system demonstration. The host site is VMC's Sandusky, Ohio, plant, a secondary aluminum smelting plant. In the VMC Sandusky Operation, the aluminum scrap material is received either by 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. The aluminum is loaded into the furnace as shown at the left side of this schematic. This charge floats on a pool of liquid aluminum and is gradually melted. Melting this charge takes 12 hours. After melting, the aluminum is alloyed and any unwanted contaminants are removed. This process takes six hours. 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 plants. This process takes about three hours.

Heat for melting the aluminum is provided by burning natural gas. Room temperature air is provided to the burners at a pressure of 8 oz/in.² by a blower. Three burners fire over the melt, each with a capacity of 8 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° to 2000°F over the production cycle.

A typical schedule for the furnace operation is shown in Figure 2.2. For the first 12 hours of the cycle, the aluminum is melted. The burners are fired at 21 MMBtu/hr and the exhaust gas temperature is approximately 2000°F. A heat balance for this operating condition is shown in Figure 2.3. Of this energy, only 6.4 MMBtu/hr are used to melt the aluminum for an overall efficiency of 30 percent. Of the balance, 11.2 MMBtu/hr (or 53 percent), is exhausted out the stack.

Figure 2.1 Aluminum Smelting Furnace

Figure 2.2 Batch Firing Schedule

Figure 2.3 Heat Balance on an Aluminum Smelting Furnace
Maximum Firing Rate (MMBtu/hr)

For the next six hours of the cycle, the firing rate of the burners is reduced to 11 MMBtu/hr. A heat balance for this condition is shown in Figure 2.4A. The exhaust gas temperature is 1800°F resulting in a stack loss of 5.5 MMBtu/hr. During standby periods the furnace is fired at 4.2 MMBtu/hr. A heat balance for this condition is shown in Figure 2.4B. The exhaust gas temperature is reduced to 1400°F, resulting in a stack loss of 1.7 MMBtu/hr.

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. 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.

The FBWHR system will be used to recover the waste heat in these exhaust gases and use it to preheat the combustion air. A schematic of this system, integrated with the aluminum furnace, is shown in Figure 2.5. The FBWHR unit is designed to provide an air preheat temperature of 1000°F at the maximum firing rate. The heat balance for the aluminum furnace with the unit installed is shown in Figure 2.6. At the maximum firing rate, the FBWHR system recovers 2.1 MMBtu/hr from the exhaust gases and uses it to preheat the combustion air. This reduces the required fuel input to 14.8 MMBtu/hr, a 30-percent reduction.

The fuel use of the furnace is 351 MMBtu/hr per charge for a specific fuel consumption of 3500 Btu/lb of aluminum. The FBWHR system will reduce this fuel use to 256 MMBtu/hr per charge, a 27-percent reduction. This results in a specific fuel consumption of 2560 Btu/lb.

2.2 DATA ACQUISITION SYSTEM

An automatic data acquisition system has been assembled to monitor the furnace operations. The system uses a Hewlett-Packard Model 85A microcomputer and a Model 3497 data acquisition module. Capabilities of this system include monitoring 40 channels of analog data and outputting 16 digital commands. The system will be installed in Sandusky to monitor furnace No. 2 operations. Specifically, air and fuel flow rates to each burner, flue gas temperature, and aluminum temperature will be monitored continuously. These data will be 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.

Two types of tests will be conducted with this system. The first is a very rapid scan of the channels that are automatically changed by the control system. This will identify the control ranges and assure that the recuperator can follow them automatically. The second test series involves a slow scan of the channels. This will provide an actual history of the furnace operations and provide the accurate data needed to construct the baseline performance curve for the furnace.

A) INTERMEDIATE FIRING RATE **B) STANDBY FIRING RATE**

Figure 2.4 Heat Balance on an Aluminum Smelting Furnace (MMBtu/hr)

Figure 2.5 Aluminum Smelting Furnace Equipped with an FBWHR System

BASELINE PERFORMANCE

PERFORMANCE WITH FBWHR SYSTEM

Figure 2.6 Heat Balance on an Aluminum Smelting Furnace with 538°C (1000°F) Air Preheat at Maximum Firing Rate (MMBtu/hr)

3. PERFORMANCE CHARACTERIZATION

Design of any fluidized-bed system requires experimental verification of the correlations being used because the extremely complex nature of the bed behavior limits the accuracy of existing correlations. During this reporting period, the analytical design tools needed to characterize the bed were developed and experimentally verified. These design tools were developed from the extensive fluidized-bed technology base available at Thermo Electron. This chapter describes the test facility, the fluidization characteristics of the heat transfer media, and the heat transfer characteristics of the fluidized bed.

3.1 EXPERIMENTAL EQUIPMENT

The laboratory test unit used in these studies is shown schematically in Figure 3.1. Figure 3.2 shows the actual installation. The heat exchanger is 1-ft wide x 4-ft long with a total height of 10 ft. The unit was constructed in four sections: a burner mount and inlet, an air plenum chamber, a fluidized-bed shell, and a disengagement section.

Vitiated air is used as the fluidizing medium with the flow circuit shown in Figure 3.3. Air is drawn from the room by an 1200-scfm forced draft fan and metered through an orifice plate. After passing through the orifice, the flow is split into two streams – one supplying air to the gas burner and the other bypassing directly into the plenum. Because the burner has a turndown ratio of 50:1, this bypass air line is used only when temperatures lower than 400°F are necessary. After exiting the fluidized bed, the gas passes through the disengagement section before being vented to the atmosphere. The shell is insulated with 2 inches of binderless insulation and outfitted with removable walls on three sides thus allowing flexibility in changing feed systems, overflow weirs, and distributor plates. A New York blower Model 144LS with a 1000°F temperature rating is used as an induced draft fan. The test material is fed into the fluidized bed through a Ducon Perma-Flow rotating air lock. The solids flow through the bed and empty over a weir at the far end.

Figure 3.1 Fluidized Bed Heat Exchanger

Figure 3.2 Preheater Model - Solids Inlet View

Figure 3.3 Laboratory Test Installation

Type K thermocouples (TC's) are used to measure all temperatures. Shielded beads are used in the bed and aspiration thermocouples used to measure all gas temperatures. Thermocouples are located in the following positions:

- One TC at the inlet to the gas burner
- Three aspiration TC's measuring gas temperature below the distributor plate
- Three bare bead TC's welded to the distributor plate
- Three TC's attached to walls of the plenum
- Ten shielded TC's in the bed measure its temperature
- Eight aspiration TC's measure existing gas temperature above the bed surface
- Three TC's on the freeboard wall
- Two aspiration TC's measuring gas temperature at the top of the freeboard
- One TC measuring gas temperature entering the exhaust fan

In total, 40 thermocouples are available for measurement and can be re-located as needed for the various tests.

Pressure measurements include gas and air orifice pressure losses, pressure loss of the distributor/bed combination, and absolute pressures throughout the system. Dampers on both the burner fan and exhaust fan allow the velocity to be accurately controlled.

3.2 HEAT TRANSFER MEDIA AND FLUIDIZATION CHARACTERISTICS

Proper selection of the circulation heat transfer media for the FBWHR system is critical to assure maximum performance and minimum maintenance. Since the media will be constantly circulated from the hot flue gases to the cool combustion air, high thermal shock resistance and low particle attrition are of paramount importance. Equally important is the ability of the material to withstand the corrosive environment of the flue gas. The material must have the following characteristics:

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

The material best suited to this application is alumina, which is a hard ceramic and is compatible with the aluminum furnace exhaust environment. It is available in several grades ranging from nonspherical low-purity commercial grade to a spherical high-purity media. For this program, nonspherical alumina ranging between 500 and 1000 microns in diameter and of approximately 95-percent purity was selected. This material is commonly available as blasting grain. If attrition, due to the jagged particles or chemical attack of the impurities, becomes a problem, high purity or spherical particles can be substituted.

When gas is passed vertically through a bed of alumina, it exerts a drag force on the particles. The pressure drop through the bed is proportional to the velocity. When the velocity is increased, the drag increases which eventually offsets the weight of the particles. This velocity is the minimum fluidization velocity (V_{mf}).

Because the particles are not spherical, the minimum fluidization velocity cannot be accurately calculated and any calculations must be experimentally verified. The best correlation for the minimum fluidization velocity is that of Wen and Yu (1962):

$$Re_{mf} = \frac{\rho_f V_{mf} d_p}{\mu} = (33.7^2 + 0.0408 Ar)^{\frac{1}{2}} - 33.7$$

where:

$$Ar = \frac{\rho_f (\rho_s - \rho_f) g d_p^2}{\mu^2}$$

This correlation was tested over a wide temperature range for the No. 24 mesh alumina blasting grain. The correlation between theoretical and experimental results was excellent, as shown in Table 3.1.

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 imparting sufficient mobility to the particles to assure a smooth flow of solids away from the feed zone and along the bed. Tests simulating the FBWHR system operating conditions indicate that a velocity of three times minimum fluidization velocity is required.

The minimum fluidization velocity varies strongly with particle diameter. Figure 3.4 illustrates this variation for 1000°F — the average temperature of the fluidized bed. The theoretical correlation of Wen and Yu was used to construct this curve. Also shown in this figure is the minimum operating velocity (three times minimum fluidization velocity) for this range of particle sizes. These curves therefore define the maximum particle diameter for a specified superficial velocity.

When the gas velocity is increased above the minimum fluidization velocity, the bed expands to maintain the drag on each particle equal to its weight. Thus, the void fraction increases with velocity. This is shown in Figure 3.5. The theoretical curve is that of Wen and Yu (1962) and the experimental points are for No. 24 mesh blasting grain. These results were obtained by placing a known weight of alumina in the laboratory unit and measuring the depth of the bed for different velocities. This depth was measured by mounting a scale on the edge of the distributor plate and recording the lowest level that the fluctuating bed surface attains. It can be seen that there is very good agreement between the experimental and theoretical results.

The maximum superficial velocity will be determined by the loss of media. For spherical particles the terminal velocity, or velocity at which the particles would be entrained by the gas, is 15 to 30 times the minimum

TABLE 3.1
COMPARISON BETWEEN MEASURED AND CALCULATED
MINIMUM FLUIDIZATION VELOCITIES

Temperature (°F)	Measured V_{mf} (ft/sec)	Calculated V_{mf} (ft/sec)
80	1.4	1.42
250	1.2	1.28
425	1.02	1.16
710	1.10	1.00
890	1.0	0.92
1160	0.90	0.85

Figure 3.4 Minimum Fluidization Velocity for Alumina Particles

Figure 3.5 Voidage of Alumina Fluidized Bed

fluidization velocity, depending on the particle size. However, significant amounts of bed material can be entrained at velocities less than terminal, reducing the operable velocity range. Generally, velocities should be less than one-half of terminal velocity to minimize entrainment. This, therefore, results in an operating range of 3 to 7 or 3 to 15 times the minimum fluidization velocity, depending on the upper limit. Tests have not been performed to quantify the elutriation although no noticeable entrainment has been observed during the laboratory testing.

3.3 HEAT TRANSFER

A fluidized bed can be modelled as a crossflow heat exchanger. Ideally, if both the gas and particles flowed through the heat exchanger without mixing, the effectiveness of the fluidized bed would be

$$\epsilon_i = 1 - \exp(-C_g/C_s)$$

where: C_s = thermal capacity of solids

C_g = thermal capacity of gases.

This is graphed in Figure 3.6. However, in a fluidized bed the movement of the particles causes the particles to mix laterally with adjacent material.

A model for the heat transfer was formulated to predict the temperature profile within the bed based on this concept. When the back mixing of the particles is modelled as an effective thermal conductivity, an energy balance on a differential element, shown in Figure 3.7, within the bed yields

$$\frac{d^2T}{dx^2} - \frac{C_s}{kwh} \frac{dT}{dx} - \frac{C_g}{kwhL}(T - T_g) = 0$$

where: x = distance along bed

C_s = thermal capacity of solids

C_g = thermal capacity of gases

T_g = gas temperature

k = conductivity of bed

w = width

h = height

L = length.

Figure 3.6 Ideal Crossflow Heat Exchanger

Figure 3.7 Temperature Profile Model

This equation was solved using appropriate boundary conditions to give the temperature profile. A family of curves is shown in Figure 3.8 for $C_g/C_s = 1.0$ and various values of the effective conductivity, k_* . When mixing is low, k_* is zero and the temperature profile is that of an ideal crossflow heat exchanger. When k_* is high, the temperature profile becomes uniform. The degree to which the profile flattens out can be altered by varying the geometric proportions of the bed. A long narrow bed would decrease the effect of having a high conductivity.

Laboratory testing has shown that this model accurately determines the temperature profile within the bed. Testing has also shown that the thermal conductivity is dependent on the superficial velocity varying from almost zero at minimum fluidization to over 5000 Btu/hr-ft-°F at 10 ft/sec.

Radiation heat losses must also be considered in the final analysis of the FBWHR system. If the radiation term is included in the differential equation, it becomes nonlinear and unsolvable explicitly. As an approximation, it is possible to superimpose a separate analysis of the radiation losses on the temperature profile. This would give an upper bound on the losses due to radiation. If a heat balance is performed on the element of bed shown in Figure 3.9, it is found that:

$$dq = (\dot{m}C_p)_s dT = \sigma \epsilon_o (T^4 - T_w^4) dA.$$

Integrating this equation, a comparison of ideal and radiation-corrected temperature profiles is made in Figure 3.10 for a typical unit. It can be seen that the radiation losses result in a decrease in the exit temperature.

In Figure 3.11, the influence of plenum wall temperature and average residence time on loss of heat from the bed is shown. In a typical FBWHR installation, the residence time of the solids will be one to five minutes. This, along with a moderate amount of insulation, will decrease the radiative energy loss to negligible levels.

Figure 3.8 Calculated Temperature Profile in Fluidized Bed

Figure 3.9 Radiation Loss Model

Figure 3.10 Radiation Heat Losses From a Fluidized Bed

Figure 3.11 Effect of Average Residence Time and Plenum Wall Temperature on Radiative Energy Losses From a Fluidized Bed Preheater

4. HOT PARTICLE FEED SYSTEM

One area critical to the FBWHR system is the feed system which feeds the hot particles from the upper bed to the lower bed. Besides feeding the particles this system must also minimize gas leakage across a pressure difference of up to 23 in. wc. Presented herein are a description of the feeder, results of preliminary experiments to verify its performance, and results of experiments to quantify the gas leakage.

4.1 FEEDER DESCRIPTION

In the upper fluidized bed the heat transfer media are fluidized by the flue gases from the furnace and heated to temperatures of up to 1600°F. These particles must then be removed from the bed, transferred to the lower bed, and injected into the lower bed. Flow rate of the media must be easily controllable and variable from 0 to 7 lb/sec. The design specifications for the hot particle feed system are shown in Table 4.1.

The requirement for minimum gas leakage is particularly hard to satisfy because of the very high pressure differential between the beds. Because the furnace must be maintained at atmospheric pressure, pressure in the hot bed freeboard will be 2 to 10 in. of water subatmospheric. However, because of burner drive pressure requirements, the pressure in the cold bed freeboard will vary from 4 to 13 in. of water above atmospheric pressure. Thus the pressure difference will vary from 6 to 23 in. wc.

A feed device capable of meeting the specifications of Table 4.1 is an L-valve. This is illustrated in Figure 4.1. The particles will leave the bed over a weir. After leaving the upper bed the particles fall into a downcomer and form a packed bed. This bed will be sufficiently deep to minimize the air leakage to the flue. A small quantity of air, called aeration air, is injected into the downcomer at the L-valve to control the particle removal rate from the downcomer and into the lower bed. Without aeration air, the particles will build up in the downcomer. At high aeration air flow rates, the particle removal rate will be high, and the inventory of particles in the downcomer will be reduced. Thus, particle flow rate is easily controlled with the aeration air.

TABLE 4.1
HOT PARTICLE FEED SYSTEM SPECIFICATIONS

Media Temperature	- Up to 1600°F
Media Flow Rate	- Variable, 0 to 7 lb/sec
Gas Leakage	- Less than 0.05 lb/sec (Combustion Air to Flue)
Media Temperature Loss	- Less than 50°F
Pressure Difference	- 6 to 23 in. wc
High Reliability	
Low Maintenance	
Ease of Control

Figure 4.1 Media Circulation System

Control methodology will be to control the aeration air to maintain a constant particle inventory in the downcomer. To implement this, a height sensor will be installed in the downcomer. Though many alternative sensors could be employed, a differential pressure sensor connected between the upper third of the downcomer and the freeboard of the hot bed is the easiest concept to implement. When this pressure decays, it means the particle inventory is being reduced, and the control system will decrease the aeration air. On the other hand, when this pressure increases, it means the particle inventory is being increased, and the control system will increase the aeration air. Total particle flow rate will not be controlled by the hot feed system, but rather by the cold particle return system.

Thus the L-valve meets all the criteria for the hot particle feed system. Of particular interest with this alternative is the lack of any mechanical moving parts which will maximize reliability and minimize maintenance requirements.

4.2 PARTICLE FEED TESTING

Laboratory tests were conducted to verify the operation of the L-valve. The test objectives were determination of particle flow rate dependence upon the aeration air flow rate, and investigation of alternative configurations. Figure 4.2 shows the experimental equipment. A description of the facility is given in Section 3.1. The L-valve was installed between the rotary valve and the distributor plate. This allowed accurate control of the particle flow into the L-valve. Five taps were provided for the aeration air which was supplied from the building compressed air supply. The L-valve was tested with both hot and cold fluidized beds.

Test results are shown in Figure 4.3 for a 2-7/16-in.-diameter tube with a horizontal section into the fluidized bed. Test results are given for three different aeration air tap locations. In all cases, a minimum aeration air flow rate must be achieved before the particles start flowing.

Figure 4.2 Schematic Showing L-Valve at 20° from Horizontal

Figure 4.3 Particle Feed Test at $\Delta_r = 0$

Once this minimum flow is achieved, the particle flow rate increases with increasing aeration. As the aeration air moves through the packed bed it exerts a drag force on the particles. The particles will not start moving until a critical drag force is achieved. For a high particle flow rate tap location (3) seems to be the best, but for control the linear characteristics of location (1) are better.

Figure 4.4 shows similar results for a feed angle of 20°. In this case the minimum aeration air flow rate has decreased since gravity is assisting in dragging the particles into the bed. In the tests with aeration at locations (1) and (2) a maximum particle flow was observed.

The design particle flow rate of 3.5 lb/sec can be achieved by using a layer feed or multiple feeds into the bed. At these flows the aeration flow constitutes approximately 1 percent of the combustion air flow.

4.3 SEALING

As previously explained, the particle feed system must feed the hot particles while simultaneously preventing excessive gas leakage. For an L-valve, a packed column of particles is used to accomplish this seal. Gas flow rate through a packed bed is most accurately calculated from the Ergun Equation:

$$\frac{\Delta P g_c}{L} = \frac{150 (1 - \epsilon_o)^2 \mu V_r}{\phi^2 \epsilon_o^3 d_p^2} + \frac{1.75 (1 - \epsilon_o) V_r^2 \rho_f}{\phi \epsilon_o^3 d_p}$$

where:

- ΔP = pressure across packed bed
- L = height of particles in tube
- g_c = gravitational constant
- ϵ_o = porosity of particles (fixed bed)
- V_r = gas velocity relative to the particles
- μ = viscosity
- ϕ = particle shape factor
- d_p = particle diameter
- ρ_f = gas density.

Figure 4.4 Particle Feed Test at $\Delta_f = 20^\circ$

All the parameters in this equation are either design or physical constants, except the gas leakage rate. Thus the leakage rate can be calculated with this correlation.

Experimental tests were conducted to verify the Ergun Equation for nonspherical alumina over the size range of interest.

These experiments were performed in a Plexiglas apparatus as shown in Figure 4.5. The box simulated the lower bed freeboard, and the tube simulated the downcomer. The box was completely sealed and the tube was open at the upper end. The tube was filled with alumina particles to a given height to simulate the packed bed. The box was pressurized, via a nitrogen bottle thus setting up a pressure differential across the packed bed. Since the box was sealed, the nitrogen flow rate into the box was equal to the leakage through the packed bed. Nitrogen flow rate, box pressure, and packed bed height were measured during the testing. Leakage tests were performed for various sizes of alumina particle diameters ranging from 0.031 in. to 0.111 in.

The experimental results and analytical predictions are shown in Figure 4.6 for 24-mesh alumina. As anticipated, the gas leakage increases with the pressure gradient. The correlation between theoretical and experimental results is best at low values of the pressure gradient and the deviation increases as the pressure gradient is increased. This is because of the experimental difficulty of maintaining a uniform pressure difference at high leakage rates.

Test results for different particle diameters are shown in Figures 4.7 through 4.9. As predicted by the theory, leakage rates increased as the particle size increased. Also, the problem of maintaining a uniform pressure difference increased. However, the correlation between theoretical and experimental results is still good.

These tests were conducted for a static bed. In the actual FBWHR system the particles will be moving downward, dragging the gas along with them and decreasing the leakage rate. Proper design of the feed tubes in terms of size and number will minimize the leakage rate. These designs are currently being pursued.

Figure 4.5 Schematic of Sealing Experiment

Figure 4.6 Leakage Test Using No. 24 Particles

Figure 4.7 Leakage Test Using No. 8 Particles

Figure 4.8 Leakage Test Using No. 12 Particles

Figure 4.9 Leakage Test Using No. 16 Particles

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5. DISTRIBUTOR PLATE

One critical component in any fluidized-bed system is the distributor plate. The purpose of this plate is to stabilize the bed by inducing a flow-dependent pressure loss. From systems requirements, this pressure loss must be minimized and the plate must survive in the environment. This is a particularly severe problem for the upper plate in the FBWHR system. This chapter describes the plate stability criteria, configuration constraints, material alternatives, and fouling experience.

5.1 BED STABILITY

One of the concerns in the design of a fluidized-bed preheater is the parasitic power requirement needed to overcome the pressure loss of the heat exchanger. To minimize this, a shallow bed is used, the minimum depth of which is determined by mechanical constraints such as fastening or warpage of the distributor plate. Once the bed depth is determined, the minimum pressure loss for the distributor plate is fixed by bed stability constraints. However, this minimum pressure loss has not previously been addressed for shallow bed applications.

The purpose of a distributor plate in a fluidized bed is twofold. First, it supports the bed material when the gas flow is turned off. Second, and most important, its pressure loss forces the gas flow to be distributed evenly over the area of the bed. The degree to which the distribution is even is dependent on the relative pressure losses of the distributor plate and the bed itself. Several investigations (Hiby, 1964; Davidson and Harrison, 1971; and Siegel, 1976) have investigated this problem for deep beds (e.g., when the depth of the bed is larger than its diameter). However, very little has been done in shallow fluidized beds.

Siegel (1976) analytically developed a criterion for stability of porous distributor plates; i.e., plates with a linear pressure loss characteristic. This analysis was modified to apply to the case of a quadratic pressure loss

characteristic typical of perforated plates. Results of this analysis indicated that the minimum pressure loss varies with material properties and operating conditions. This variation with superficial velocity is shown in Figure 5.1. The minimum pressure loss ratio varies from 0.3 to 0.5 over the potential operating range of the preheater. For a 3-in. expanded bed depth, total pressure loss across the preheater could therefore be as little as 6.0 in. wc.

Experiments were performed to determine the nature of the instability itself. This was accomplished by maintaining constant test conditions (velocity and temperature) and observing the fluidization of the bed as the bed depth was increased. As the depth of the bed increases, the pressure loss increases and the ratio ($\Delta P_D / \Delta P_B$) decreases, pushing the system into the unstable regime. Figure 5.2 shows experimental results. In Tests I and III,* the bed should be in stable fluidization according to the theory. Observations revealed that all areas of the bed were evenly fluidized and pressure loss readings were steady. However, in the other tests, as the depth of the bed was increased the bed became unstable and channeling occurred. As the bed depth increased, the fluctuations of pressure became more severe and some segments of the bed became defluidized and stagnant. This is as predicted by the theoretical analysis. Further experimentation is necessary to accurately determine the operating limits for the FBWHR system.

5.2 PLATE CONFIGURATION

Perforated plates will be used for the distributor plates in the FBWHR system. Though other configurations could have been selected (bubble caps, slotted plates) their features are not required for this system. Perforated plates have the advantages of ease of fabricability and specification.

*A test consists of all the points arranged vertically in Figure 5.2. Test I has two points, Test II has six points, etc.

Figure 5.1 Pressure Drop Ratio as a Function of Velocity for Alumina

Figure 5.2 Experimental Data Range for Pressure Drop Ratio

The flue gas temperature the plate experiences ranges between 1400° to 2000°F with occasional higher excursions. The plate must also withstand substantial temperature transients and, to some extent, temperature gradients. The design temperature of the plate is important since it determines the mechanical properties of the plate material. The plate temperature may be somewhat lower than the nominal gas temperature since both the plate and the gas radiate to the recuperator shell.

A one-dimensional steady-state model, shown schematically in Figure 5.3, was used to calculate the plate temperature. The dominant heat transfer mechanism is the convective loading in the plate holes due to the high heat transfer coefficient. Figure 5.4 shows the results of the calculations as a function of plate area and shell insulation. At an area of 20 ft², the plate temperature can be as low as 1700°F or as high as 1950°F, depending upon how well the freeboard and plenum are insulated.

As stated in the previous section, the minimum pressure drop across the plate is related to the bed pressure drop. This relationship is needed to maintain a stable bed. Knowing the pressure drop both the open area and plate area can be calculated for a given mass flow rate. The percent open area is the open area divided by the plate area. The percent open area is given in Figure 5.5 as a function of total pressure drop and plate area. Figure 5.6 shows the relationship between the percent open area and the hole spacing.

It is desirable to make the hole diameter as large as possible in order to:

- Minimize fouling problems
- Minimize fabrication difficulties

However, the maximum hole diameter is limited due to particle fall through. A hole diameter equal to about 2½-particle diameters is generally considered adequate. A 2½-particle-diameter rule and 800-μm particles would require the hole diameters to be not much larger than 1/16-in.

Figure 5.3 Heat Loading on Upper Distributor Plate

Figure 5.4 Control of Plate Temperature with Wall Insulation

Figure 5.5 Variation of Open Area with Distributor Plate Pressure Loss and Cross Section

A-6630

Figure 5.6 Hole Pitch

5.3 MATERIALS SELECTION

The procedures used to select suitable materials for the distributor plate are discussed in this section. Compounds of chlorine, sodium, and potassium as well as products of combustion exist in the flue gases. By far, the most critical component in the design is the upper distributor plate. It must withstand a high temperature, corrosive gas environment, and also accommodate internal temperature gradients.

Chlorine is injected into the aluminum melt where it combines with unwanted magnesium to be later skimmed off. If any of it escapes into the furnace it will readily combine with the water vapor to produce hydrochloric acid. The process is controlled by the disassociation of the water. Figure 5.7 is an equilibrium calculation showing the amount of HCl produced as a function of the amount of Cl_2 entering the furnace, and temperature. At 1000°F, however, there will be some free Cl_2 in the gases. Therefore the distributor plate must be immune to attack from HCl and Cl_2 .

Several alternative materials are being evaluated for use as the hot bed distributor plate. Silicon carbide (SiC) is especially attractive because of its excellent thermal shock resistance. Other ceramics are also attractive in terms of their corrosion resistance and high-temperature properties but tend to have thermal shock problems. A high-temperature metal, such as Inconel combined with a corrosion-resistant coating, is also being considered since it offers fabrication advantages.

5.3.1 Silicon Carbide

The excellent mechanical properties of SiC are shown in Figures 5.8 and 5.9. Figure 5.8 shows the strength of SiC to be unaffected by temperature up to about 2460°F. Figure 5.9 shows the sintered SiC to be weaker than that shown in Figure 5.8, but nonetheless adequate for the recuperator. Not shown in any of the figures is the hysteresis effect of bonded SiC. Temperature excursions may allow the bonding agent to be vaporized and lost thus rendering the base material somewhat weaker. The actual strength degradation is unknown, but the effect is cumulative.

Figure 5.7 Hydrochloric Acid Production from Chlorine Injection - Equilibrium Calculation

Figure 5.8 Mechanical Properties of Silicon Carbide

Figure 5.9 Stress Rupture Life of SiC and Si_3N_4

There is a potential corrosion problem associated with the use of silicon carbide. Currently no information exists on the corrosion of silicon carbide in flue gases. However, some information is available concerning various phenomena associated with the corrosion of silicon carbide.

Figure 5.10 shows the corrosion characteristics of silica bonded silicon carbide in a pure chlorine environment (Carborundum). Inconel is shown for a comparison in the same figure. At the plate design temperature, the corrosion of silicon carbide would be unacceptable. However, the actual flue gases contain chlorine in only low concentrations. It is also known that silicon carbide forms a protective silica layer in the presence of oxygen. This layer enhances its corrosion resistance. The existence of this layer will be affected by the sodium and potassium compounds in the flue gases. These compounds can affect the viscosity of the silica layer allowing it to run off.

A major disadvantage of SiC is the restricted sizes available in plate form. Table 5.1 lists sizes as quoted from various manufacturers. Since a plate of approximately 20 ft² is required, it will be necessary to join several of the plates together. Consider Norton's 2- x 1½-ft plate. If the 2-ft dimension is taken as the width of the bed, a total length of 10 ft would be used. This requires joining seven plates end to end. Alternatively, the 1½-ft dimension can be taken as the width, yielding an aspect ratio of 9.3 and a length of 14 ft.

The plates can be joined, as shown in Figure 5.11. It is necessary that the leakage at the joint be controlled to assure particle fluidization. Too low of a leakage would allow stagnant zones to form above the joints impeding the particle flow. Too high a leakage would cause stagnant zones to appear elsewhere in the bed.

As shown in Section 5.2, it is necessary to have many closely spaced holes in the plate. Because of the hardness and low electrical conductivity of SiC, it is not possible to drill or electrically machine the plate after

Figure 5.10 Corrosion of Silicon Carbide and Inconel in Chlorine

TABLE 5.1
AVAILABLE SILICON CARBIDE SIZES

Norton Ceramics	$2 \times 1\frac{1}{2} \text{ ft}^2$
Carborundum	$1 \times 1 \text{ ft}^2$ (3/8 in. Minimum Thickness and Retooling Required)
Atomergic Chemetals	$\frac{1}{2} \times \frac{1}{2} \text{ ft}^2$ (1 in. Thick)
Coors Porcelain	$\frac{1}{2} \times \frac{1}{3} \text{ ft}^2$

Figure 5.11 Joining of Ceramic Distributor Plates Allowing Controlled Leakage

fabrication. Laser drilling is also unacceptable since it will induce local thermal stresses that may crack the plate. The holes must be put in during fabrication. Not all vendors have this capability, restricting further the plate sizes and bonding agents available.

5.3.2 Inconel

It is possible to avoid the fabrication and size problems of SiC by employing a high-temperature metal coated with a corrosion-resistant layer. A review of coating technology is given by Swaroop (1976). A typical diffusion-bonded coating is shown in Table 5.2. Once oxidized to alumina, an aluminum diffusion coating is highly corrosion resistant and is adequate to protect the metal.

Unfortunately the coating can spall off, exposing the subsurface to the flue gas. The replenishing nature of the coating softens the impact of the problem. If the layer were completely eroded, the bare exposed metal would not survive in the flue gas.

One problem with Inconel is the poor stress rupture life, as shown in Figure 5.12. At the plate design temperature, only a minimal amount of stress is tolerable. Comparing this to Figure 5.9 clearly shows the advantage of ceramics.

5.3.3 Alumina

Alumina is chemically one of the most stable refractory compounds. Up to 3300°F it is resistant to all gases except moist fluorine (Clancy, 1981). In addition, compared to SiC, it is easily machined. This makes it attractive for use as a distributor plate.

The alumina plate sizes that are available are similar to SiC, as shown in Table 5.3. The discussions on SiC plate size apply for alumina as well.

The thermal shock resistance of alumina is probably its severest disadvantage. Thermal shock resistance of materials can be compared using (Davidge, 1967)

TABLE 5.2
METAL COATING

- Purpose
 - Protect Metal from Corrosive Attack
- Type
 - Aluminum Diffusion Coating
 - 10% Aluminum
 - 2% Chloride Activator
 - Balance Alumina
- Depth
 - $\frac{1}{2}$ to 5 mils
- Maximum Size
 - $7 \times 3\frac{1}{2} \text{ ft}^2$
- Protection
 - Protects Metals Against All Corrosive Agents Found in Furnace

Figure 5.12 1000-Hour Stress Rupture Life

TABLE 5.3
AVAILABLE ALUMINA SIZES (>95% PURE)

Harbison-Walker	$1\frac{1}{2} \times 1\frac{1}{2} \text{ ft}^2$ (1 in. Minimum Thick)
American Feldmuehle	$\frac{1}{3} \times \frac{1}{3} \text{ ft}^2$ (1 in. Minimum Thick)
National Ceramics	$1 \times \frac{1}{2} \text{ ft}^2$ ($\frac{3}{8}$ in. Minimum Thick)
Coors Porcelain	$1 \times 1 \text{ ft}^2$ (1 in. Minimum Thick)

$$R = \frac{(1 - D) K}{\epsilon \alpha}$$

where:

- ϵ = Young's modulus
- α = coefficient of linear expansion
- D = Poission's ratio
- K = thermal conductivity.

Large values of R yield high thermal shock resistance. The desirable properties of a material are high values of thermal conductivity and low values of coefficient of expansion. As an example, the ratio of K/α of alumina to that of SiC is 0.07, showing the relative poor thermal shock resistance of the former.

5.3.4 Other Ceramics

The thermal shock of other ceramics are as poor as, or worse than, alumina. In addition, they are not as corrosion resistant as alumina. For that reason, they are not acceptable materials for the FBWHR system.

5.3.5 Materials Summary

Table 5.4 summarizes the advantages and disadvantages of the three candidates. Silicon carbide is the best choice as long as the plate can be fabricated with the desired percent open area. Inconel is an excellent short-term material, but may not be adequate for long periods of time. The poor thermal shock of alumina relegates it to a third position.

Two materials, a primary and backup, will be carried throughout the program. Currently, SiC is being considered for the primary and coated Inconel for the backup.

5.4 MATERIALS EXPOSURE TESTING

Exposure testing of alternate materials is being conducted in the furnace flue at VMC. The materials being exposed are silicon carbide and pure alumina. Figure 5.13 is a photograph of the materials holder with samples in place.

The samples were examined after one week of exposure. One of the alumina samples had cracked in half, which was probably due to thermal shock. The densities of all the samples were unchanged indicating no major chemical reactions had occurred. However, longer exposure times will be needed for meaningful results. Additional tests are planned in conjunction with Oak Ridge National Laboratories. A wider variety of samples will be used.

5.5 FOULING TESTS

The flue gas environment and the small holes in the distributor plate raise the possibility of plate fouling. To determine the magnitude of the problem a long-term test is being conducted on the host site's No. 2 furnace. The experiment is shown schematically in Figure 5.14. Flue gases are drawn from the flue and through a 1½-in.-diameter distributor plate using a jet pump. The flue gas flow rate is controlled by a pressure regulator on the air supply line to the jet pump. Vacuum pressure is monitored and periodic inspections of the plate are conducted.

After more than 200 hours of testing, all the central holes were open. One hole, on the perimeter, was plugged. This may not be important since the flow and temperature close to the wall of the holder are not typical of the full-scale unit. Although the experiment indicates fouling is not a problem under the tested conditions, more significant testing is needed to establish the fouling susceptibility of the flue gases.

TABLE 5.4
CANDIDATE MATERIAL COMPARISON

- Silicon Carbide
 - Advantages
 - . Resistant to Hydrochloric Acid
 - . Good Thermal Shock Ability
 - . Mechanical Properties Constant with Temperature
- Inconel with Coating
 - Advantages
 - . Large Size Available
 - . Resistant to Corrosive Attack
 - . Relatively Easy to Machine
- Alumina
 - Advantages
 - . Resistant to Corrosive Attack
 - . Mechanical Properties Constant with Temperature
- Silicon Carbide
 - Disadvantages
 - . Susceptible to Chlorine Attack
 - . Limited Size Available
 - . Difficult to Machine
- Inconel with Coating
 - Disadvantages
 - . Poor High-Temperature Stress Rupture Life
 - . Will Corrode if Coating Spalls
- Alumina
 - Disadvantages
 - . Poor Thermal Shock Ability
 - . Failure Could be Sudden
 - . Limited Size Available

Figure 5.13 Materials Holder

Figure 5.14 Fouling Test

6. SUMMARY AND FUTURE WORK PLAN

Work on this program was initiated during this reporting period. Three different areas were pursued: Laboratory Development, Design Analysis, and Host Site Characterization. During Laboratory Development, the hot particle feed system development was initiated, distributor plate stability was determined, and media fluidization characteristics were determined. In the Design Analysis, the distributor plate stability criteria were developed, heat losses were estimated, and alternative materials for the hot distributor plate were investigated. For the Host Site, a data acquisition system was assembled, a fouling test was performed, and material samples were placed in the exhaust gas flue. Thus the background information and design tools necessary to design the FBWHR system have been developed.

Over the next six months, effort will focus on designing the system. Specifically:

- The systems analysis will be completed. This includes sizing the beds, finalizing the turndown option, and specifying the pressure loss characteristics.
- The conceptual design will be completed. This will define the final design concepts to be implemented. Specific concerns include the pumping system, control methodology, particle return concept, and distributor plate options.
- Major long lead time material will be specified and ordered. Specifically identified critical items include fans, burners, distributor plate, and controls.
- Fouling and material exposure testing will continue.

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7. REFERENCES

- Anonymous, Aluminum Statistical Review, The Aluminum Association, 1976.
- Carborundum Property Data Sheet on KT Silicon Carbide.
- Clancy, T.A., "High Temperature Corrosion Resistance of Ceramic Materials," Bureau of Mines Information Circular 8843, 1981.
- Davidge, R.W. and Tapping Co., "Thermal Shock and Fracture in Ceramics," Trans., Brit. Ceramic Soc., 66, 1967.
- Davidson, J.F. and Harrison, D., Fluidization, Academic Press, New York, 1971.
- Ergun, S., "Fluid Flow Through Packed Columns," Chemical Engineering Progress Symposium Series, 4 (2): 89, 1952.
- 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.
- Hiby, J.W., "Critical Minimum Pressure Drop of the Gas Distribution Plate in Fluidized Bed Units," Chem. Engr. Tech. Vol. 36, pp. 228-229, 1964.
- Siegel, R., "Effect of Distributor Plate-to-Bed Resistance Ratio on Onset of Fluidized Bed Channeling," AIChE Journal, Vol. 22, No. 3, pp. 590-592, May 1976.
- Starper, J.W. and Kurtz, H.F., Mineral Facts and Problems, Bureau of Mines Bulletin No. 667, 1975.
- Swaroop, R., "Ceramic Coatings for Components Exposed to Coal-Gas Environments: A Review," Argonne National Laboratory Report ANL-76-124, 1976.
- Wen, C.Y. and Yu, Y., "Mechanics of Fluidization," Chemical Eng. Prog. Symp. Series, No. 62, Vol. 62, pp. 100-111, 1962.