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FLUIDIZED-BED WASTE-HEAT RECOVERY SYSTEM DEVELOPMENT

Semiannual Report for August 1, 1982—January 31, 1983

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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

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. 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, most 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 Numbers DOE/ID/12302-1 and -2, include:

- Distributor Plate Fouling Tests;
- Initiation of Material Coupon Tests;
- Characterization of Furnace Operations;
- Analytical Development and Experimental Verification of the Distributor Plate Stability Criteria, Fluidization Characterization, and Heat Transfer Characteristics;
- Completion of the FBWHR System Conceptual Design and Hardware Specifications; and
- Development of the Medium Feed System to Transfer Medium from the Hot to the Cold Bed.

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

- Fabrication, Laboratory Testing, and Field Installation of a Fluidized-Bed Fouling and Corrosion Test Unit;
- Fabrication of Several Alternate Distributor Plate Cleaning Systems for Use in the On-Site Test Unit;
- Continued Coupon Tests of Aluminum Diffusion-Coated Inconel 625 in Vulcan Materials Company's Flue;
- Identification and Procurement of Alternate Distributor Plate Alloys and Coatings to be Tested in Vulcan Materials Company's Flue, and,
- Design of the Laboratory Test Facility

The remaining technical concerns of this program have been identified and solutions are under development. These are:

- 1) Distributor Plate Fouling - A field test unit will be installed in an aluminum plant to determine the extent and nature of the fouling and, if necessary, methods to clean the plate will be tested.
- 2) Distributor Plate Corrosion and Life - In addition to the field test unit, several coupon samples will be tested in the flue.
- 3) System Integration - A laboratory facility will be fabricated to complete the development of the dual fluidized-bed arrangement.

In conclusion, the FBWHR system fulfills a real need: waste-heat recovery from high-temperature, dirty, corrosive furnace exhaust gases. Efforts to develop the technology needed to build this system are continuing.

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1. INTRODUCTION

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.

*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 evaluate 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 evaluation 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 purchases. 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 chlorine 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 Materials Company (VMC) will host the field testing 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).

Figure 1.4 Fluidized-Bed Air Preheat System

of aluminum, tin, zinc, and lead. Their aluminum operations are the subject of the field tests in this 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 for the field tests. 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 and fabrication of the FBWHR field testing. Specifically:

- The field test unit, designed to address the remaining problems of distributor plate fouling, corrosion, and stress rupture life, has been fabricated. Laboratory testing of this unit has been completed. Installation of the unit at the host site and initial field testing has been accomplished.
- Distributor plate alloys and coatings, to be coupon tested in VMC's flue, have been received and fabrication begun.
- Design of the laboratory test facility has been completed.

Details of these accomplishments are presented in this report.

Figure 1.5 Aluminum Smelting Furnace

Figure 1.6 Aluminum Smelting Furnace Equipped with an FBWHR System

2. FIELD TESTS

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

2.1 UPPER DISTRIBUTOR PLATE MATERIALS TESTING

2.1.1 Background

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 ft²;
- Be reasonable in cost; and
- Be maintenance free for periods of one year or more.

The material identified as potentially meeting these criteria is aluminum diffusion-coated Inconel. Bare metals are not acceptable because of a lack of corrosion resistance. Alumina, an excellent corrosion-resistant material, is not acceptable because of its poor thermal shock resistance. Silicon carbide is not acceptable due to its high cost and fabrication risk. Other ceramics are also unacceptable because of either their poor thermal shock resistance, poor corrosion resistance, or poor fabricability.

The coated Inconel plate is the best identified material. The coating consists of aluminum, diffused about 5 mils into the base material.

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. 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 evaluate this material in the flue gas environment, a 1-ft² piece of aluminum diffusion-coated* perforated Inconel 625 was inserted in Vulcan Material Company's (VMC) No. 2 furnace. Flue gas temperatures for the first 911 hours were typical of furnace operation. 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 2.1. For comparison, a photomicrograph of an unexposed sample is shown in Figure 2.2. The top micrograph of Figure 2.1 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 coated Inconel sample, along with a simultaneously exposed uncoated Inconel sample, was again inspected after 2250 hours of exposure in VMC's flue. A typical photomicrograph of the coated sample is shown in Figure 2.3. The coating was mostly protective although a small amount of corrosion had occurred on the substrate - about 0.0065-in. deep. The design distributor plate thickness is 0.125 in. so that the damage represents a 5-percent reduction in thickness.

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

Worst: Approximately 50% Life Used

Average: Approximately 30% Life Used

Best: Approximately 20% Life Used

Figure 2.1 Photomicrographs of Exposed Coated Inconel

Figure 2.2 Photomicrograph of Unexposed Coated Inconel

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Figure 2.3 Photomicrographs of Exposed Coated Inconel 625 (2250 Hours)

The coated Inconel sample can be compared to the uncoated exposed Inconel sample. A photomicrograph is shown in Figure 2.4. The corrosion depth on the uncoated sample was about 0.03 in. - an increase in damage over the coated sample by a factor of 4-1/2.

A third sample of the coated Inconel sample was removed from the flue after 3200 hours of exposure. In addition to the 3200 hours of exposure during furnace operation, the sample was also in the flue for 2000 hours in which the furnace was not operating. During this period the temperature of the sample was ambient, possibly leading to condensation of corrosive gases in the sample. This may artificially increase the sample corrosion rate. A visual inspection showed the plate to have no visible damage and to be functionally unaffected.

It is concluded that the coating on the Inconel 625 offered significant protection to the base metal and that the alloy-coating system is a viable material for use as a distributor plate.

2.1.2 Additional Coupon Tests Currently in Progress

The aluminum diffusion-coated Inconel 625 has been exposed continuously in VMC's flue for over 3200 hours. The excellent results from this testing have shown that coated alloys are viable candidates for distributor plate materials. However, there are several alternate coating-alloy systems that may also survive in this environment. Thus, an expanded test program is justified. The systems to be tested consist of alloys with either improved strength or corrosion resistance and alternate coatings. The testing will be conducted in the flue of VMC's No. 2 furnace.

A list of metals and coatings to be tested is given in Table 2.1. The aluminum diffusion-coated Inconel 625 has been tested for over 3200 hours and will continue to be tested along with the other samples. It will serve as a basis of comparison for the other samples. Generally, the higher the alloy strength, the lower its machinability. Inconel 625 was chosen because of its compromise between strength and machinability. Both are

Figure 2.4 Uncoated Inconel 625 Exposed for 2250 Hours

TABLE 2.1
CONTINUED COUPON TESTING TEST PLAN

- Coated Inconel 625 (Coatings Technology Co.)
- Other Alloys
 - Haynes Alloy 188 (Improved Corrosion, Higher Strength)
 - Inconel 601 (Improved Corrosion)
 - Cabot Alloy 214 (Self-Coating)
 - 316 Stainless Steel (Low Cost)
- Coating Manufacturers
 - ALON Processing, Inc.
 - Aremco Products, Inc.
 - Refractory Corporation

adequate. Haynes Alloy 188 has higher strength than Inconel 625 at elevated temperatures. At design temperature, Haynes Alloy 188 is about 75 percent stronger than Inconel 625. Stainless Steel 316 was chosen due to its increased machinability.

Alloys that have improved corrosion resistance over Inconel 625 are Haynes Alloy 188 and Inconel 601. These alloys augment the corrosion protection of the coating. Once the coating is depleted the alloys themselves offer corrosion resistance thus extending the life of the distributor plate. The distributor plate life is then equal to the combined lives of the coating and alloy.

Cabot 214 (formerly designated 8174), also included in the test program, is a self-coating metal which eliminates the need for a coating process. This material continuously produces an aluminum oxide scale during operation.

Testing of alternate alloys will be complimented by testing of alternate coatings. Two types will be tested. First, an aluminum diffusion coating produced by ALON Processing, Inc. This is the same coating used with Inconel 625 but produced by a different manufacturer. This will allow variances in coating properties due to different vendor techniques to be determined. Second, coatings generically different from the current coating will be tested. This will determine the survivability of alternate coatings in this environment. In all, 10 samples will be tested. The combination of alloys and coatings is shown in Table 2.2.

A comparison of the results between the different alloys and between the coatings will be conducted in the following manner:

- Alloy Comparison

A sample of each of the candidate alloys, Inconel 625, Haynes 188, 316 SS, and Inconel 601, has been coated using the ALON process. The effect of the ALON coating is the same on each

TABLE 2.2
MATERIAL COUPON COATINGS AND FABRICATION

Coating	Alloy	Perforated
Coatings Technology	Inconel 625	Yes
ALON	Inconel 625	Yes
	Haynes 188	No
	316 SS	No
	Inconel 601	No
Refractory Corporation	Inconel 625	Yes
	316 SS	No
Aremco	Inconel 625	Yes
	316 SS	No
None	Cabot 214	Yes

alloy, hence any corrosion rate difference between the four samples will be due solely to the difference in alloys or alloy-coating bonding.

- Coating Comparison

Four samples of Inconel 625 have been coated by one of the candidate coating processes: Coating Technology, ALON, Refractory Corp., and Aremco. The effect of the Inconel 625 on the coating-alloy system will be the same in each of the four cases, hence any corrosion rate difference between the four samples will be due solely to the differences in coatings. In addition, three samples of 316 SS have been coated with the three new coating processes: ALON, Refractory, and Aremco. This will yield a second comparison of these three coatings.

The distributor plate design calls for 1/16-in.-diameter holes on 1/4-in. centers yielding about 45,000 holes in the full-scale unit. The flue gas passes through each of these holes so that corrosion of the hole internal circumference is possible. The coating, then, must cover this inner circumference as well as the plate's flat surface. To determine whether the candidate coatings have adequately covered the hole inner circumferential length, one alloy with each of the four coatings was perforated with a typical hole pattern. After adequate exposure to the flue gases, the hole's internal surface will be examined along with the plate's flat surface.

The material samples will be held vertically in the flue using the clamping holder shown in Figure 2.5. This is the same design used to hold the aluminum diffusion-coated Inconel 625 sample. That holder has withstood the flue gas environment for over 3200 hours with no indication of failure. This is mainly due to the material used (bare Inconel 625) and the large cross-sectional area of the structural members (4 in. x 2 in.). Even though corrosion is significant in this holder its large cross-sectional area eliminates stress-corrosion problems.

Figure 2.5 Material Coupon Test Holder

Each sample will have a thermocouple attached to it that will either be recorded continuously by the data acquisition system or intermittently by manual logging of a readout device. In addition, the furnace operation will be monitored continuously by the data acquisition system so that coupon test results can be correlated to furnace operations.

Periodically, the samples will be retrieved and pieces cut off according to the approximate schedule shown in Table 2.3. The cut pieces will be sent to ORNL for micrograph and elemental distribution analysis.

2.2 UPPER DISTRIBUTOR PLATE FOULING

2.2.1 Background

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. Reduction in the flow rate at high fire reduces the recuperator effectiveness and, hence, combustion air preheat temperature. 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 2.6. The internal fouling experiment consisted of a 1-1/2-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 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 2.7.

The external experiment, shown in Figure 2.8, 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

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TABLE 2.3
SAMPLE RETRIEVED

1.	350 hours
2.	725 hours
3.	2000 hours
4.	4000 hours
5.	6500 hours

Figure 2.6 Fouling Experiment Locations

Figure 2.7 Internal Fouling Experiment

Figure 2.8 External Fouling Experiment

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. 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 2.9 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 2.4. 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, in the aluminum scrap, and in the refractory walls.

The second fouling experiment, external to the flue, was inspected after 200 hours of operation and showed no fouling. A later check after 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 2.4. 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.

Figure 2.9 Distributor Plate Hole Fouling

TABLE 2.4
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

These two experiments did not show conclusively the susceptibility of the FBWHR system to fouling. Rather, they showed 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.

2.2.2 Fouling Test Unit

The purpose of the on-site fouling test unit is to develop a distributor plate system capable of withstanding the dirty, corrosive, high-temperature environment of secondary aluminum melters. This is accomplished by:

1. Monitoring the distributor plate pressure drop while controlling the gas flow rate to determine the nature and extent of fouling. If the pressure loss deviates significantly from its design value, various cleanup techniques will be used on the distributor plate to determine the most effective cleaning method.
2. Monitoring the distributor plate stress rupture life and corrosive characteristics. If either are beyond acceptable limits, alternate distributor plate materials will be tested.

2.2.2.1 Test Unit Description

● Flow Path Description

The test unit will be a 1/10-scale hot heat exchanger. A 1/10-scale unit uses 1/10 of the flue gases that would be used in the full-scale unit and 1/10 the cross-sectional area. On a linear basis, the test unit's scale is about 1/3. The 1/10-scale test unit, for conducting the corrosion and fouling testing, is shown schematically in Figure 2.10. The overall dimensions of the fluidized-bed shell are 44 in. x 20 in. with a height of 51 in. The unit was installed at VMC's Sandusky, Ohio, facility on Furnace No. 2.

Figure 2.10 Fouling Test Unit

Ten percent of the total flue gases from the furnace are passed through the unit by a 174 LS New York exhaust blower with a 10-hp motor. The flue gases enter the plenum of the unit, pass through the distributor plate, and then exit the freeboard before being exhausted out into the furnace stack.

The temperature of the flue gases entering the unit is controlled by the length of the inlet duct and the amount of insulation in it. An automatically controlled air bleed is included in the inlet duct to assure maintenance of the test unit inlet temperature during the occasional furnace temperature excursions known to occur.

A dilution valve is located immediately upstream of the fan. This allows ambient air to be mixed with the flue gases at a controlled rate so that the fan temperature remains at 500°F. Going much below this would cause condensation corrosion problems and going much above it would exceed the fan temperature limitations.

The flow rate through the distributor plate remains fixed at about 350 scfm yielding a superficial velocity of 3.5 ft/sec. The occasional flow of plenum bleed air will amount to 10 percent or less of the total unit flow rate and will not affect the superficial velocity as an automatic flow control system keeps the total flow rate fixed. The dilution valve upstream of the fan flows between 400 to 1400 scfm of ambient air.

Table 2.5 lists the design operating conditions of the unit. Fluidization and preheat characteristics, as determined by the gas temperature and superficial velocity, will be exactly matched to the full-scale unit values. Parameters affecting the distributor plate and media corrosion, stress, and fouling such as gas temperature and composition, and plate pressure drop will also be matched.

- Hardware Description

Aluminum diffusion-coated Inconel 625, described in Section 2.1.1, is used as the distributor plate material. This material-coating system

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TABLE 2.5
1/10-SCALE OPERATING CONDITIONS
AT FURNACE HIGH FIRE

	Design
Plenum Gas Temperature	2000°F
Distributor Plate Temperature	1900°F
Superficial Velocity	3.5 ft/sec
Flow Rate	310 scfm
Distributor Plate Pressure Drop	6 in. of H ₂ O
Plenum and Freeboard Heat Losses	40°F
Maximum Plenum Bleed Air	50 scfm
Fan Dilution Air	800 scfm

was coupon tested in the flue for over 2200 hours and showed excellent life and corrosion resistance. Hence, it is expected that no corrosion problems will occur.

The insulation in the unit is a surface-mortored fiberfrax; the same material used in places within the furnace. The material is resistant to the corrosive high-temperature environment of the flue gases and provides significant thermal insulation; 6-in.-thick insulation reduces the plenum-freeboard heat losses to 2 percent of the total gas heat content.

The shell of the unit is carbon steel and the uninsulated piping connecting the freeboard to the exhaust blower is stainless steel. Twelve-in. aluminum flexible tubing connects the blower exit to the flue.

The fluidized bed media consists of pure alumina (greater than 99-percent purity). This contrasts with the impure blasting grain previously employed in the laboratory testing. This will eliminate any possibility of the flue gases reacting with the impurities of the alumina. The pure alumina should be stable and non-reactive to the flue gases.

● Control Description

Flow and temperature control of the unit is completely automated so that it can operate unattended. This is accomplished by using six Honeywell controllers, three proportional (three modes - PID) and three high/low limit controllers. Figure 2.11 shows the control logic for the proportional controllers. Two of the proportional controllers activate the dilution air valve and bleed valve for the fan and plenum cooling, respectively. One proportional control operates an outlet damper that determines the flow rate. Three high/low limit controllers (not shown in the figure) provide over and under temperature protection by shutting down the fan if any of the critical temperatures move past a pre-setpoint. With the fan shut down, the flue gases will not flow through the unit, allowing it to cool. One limit control will shut down the fan if the furnace shuts down. This assures that the unit will not draw in ambient air thus minimizing condensation corrosion problems.

Figure 2.11 Fouling Test Unit Control System

- Instrumentation Description

Evaluation of the unit's performance will be conducted with instrumentation monitoring and inspections. Instrumentation is included to measure the gas flow rate, pressure drop across the distributor plate, and temperature measurements throughout the flow path. These measurements will be continuously recorded with the data acquisition system currently being used at the host site.

Ten type-K thermocouples located in the plenum and freeboard, as shown in Figure 2.12, measure the gas and wall temperatures. This allows the gas temperature and heat losses to be accurately determined.

The flow is held fixed by the control system and is determined by measuring the gas temperatures and pressure drop across a calibrated orifice. The orifice pressure drop is sensed with a 0- to 5-in. Honeywell pressure transmitter and magnehelic pressure gauges.

A Viatran 0- to 20-in.-wc pressure transmitter and magnehelic pressure gauge also measure the pressure drop across the distributor plate. Hence, with a controlled and known flow rate, any fouling that occurs would be manifested by an increasing distributor plate pressure drop.

Fouling and other problems associated with the distributor plate will also be uncovered by partially disassembling the test unit weekly (or more frequently, if needed). The distributor plate will be inspected for evidence of fouling, cracking, corrosion, or other problems. Also, the condition of the media and other test unit components will be examined at that time.

The weekly inspections will be conducted by local engineering consultants trained by Thermo Electron. As required, Thermo Electron personnel will visit the site for complete periodic inspections. Finally, daily inspection without any disassembly, will be conducted by VMC personnel also trained by Thermo Electron.

(a) Instrumentation

(b) Instrumentation within Plenum and Freeboard

Figure 2.12 Instrumentation Location

- Cleaning System Description

Previous extraction tests, conducted on VMC's flue, indicated the possibility of distributor plate fouling during operation. In anticipation of such fouling during operation of the fouling unit, several on-line distributor plate cleaning systems have been installed on the unit. The design of these systems was based on Thermo Electron's experience with distributor plate fouling in the glass industry and on the knowledge gained from the extraction tests. The systems considered, listed in Table 2.6, are either mechanical or chemical in nature. They will either dislodge the fouling material, as in the case of a mechanical rapper, or chemically change the material, as in the flue gas pretreatment. The Water-Spray uses both mechanical and chemical means since it can dissolve the material as well as mechanically dislodge it.

Of those listed, four cleaning systems have been fabricated for field testing: Water-Spray, Air Lance, mechanical wiper, and mechanical rapper. In addition, the technique of flue gas pretreatment will be considered as soon as a fouling sample from the test unit is obtained and analyzed.

The four cleaning systems fabricated for initial field testing are shown in Figures 2.13 and 2.14. Figure 2.13 shows both the air lance and water spray. The Air Lance consists of a 1/16- or 1/8-in.-diameter nozzle at the end of a 1/4-in. stainless steel tube. The tube fits through the side of the plenum wall so that the nozzle is positioned in the plenum directly under the distributor plate. The opposite end of the tubing is connected to a high-pressure air supply. The distributor plate cleaning is accomplished by the high velocity air, generated by the nozzle, as it impacts the distributor plate. The impact force can be controlled by varying the air pressure, altering nozzle diameters, or positioning the nozzle at varying distances from the plate. The entire distributor plate can be cleaned by manually translating and rotating a single air lance.

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TABLE 2.6
ALTERNATE CLEANING TECHNIQUES

- Water-Spray
- Air or Steam Lance
- Acoustical
- Mechanical
 - Wiper
 - Rapper
- Flue Gas Pretreatment

Air Lance

Water Spray

Figure 2.13 Cleaning Systems

Mechanical Rapper

High Temperature Wire Brush

Figure 2.14 Mechanical Cleaning Systems

The water spray is similar to the air lance in that it also uses impact force to dislodge the particles. In addition, the water will also dissolve any water-soluble material thus increasing its cleaning effectiveness. A Spraco water nozzle is connected to 1/4-in. stainless steel tube in the same plenum position as the air lance. High-pressure water is supplied to the tube and flows through the nozzle. The water spray system can cover the entire distributor plate in a fashion identical to the air lance.

The disadvantage of the water spray is the possibility of thermal shock it may impart to the distributor plate. The distributor plate design temperature is 1900°F and the water spray temperature can be from 32° to 60°F. The water will vaporize as it hits the plate, locally cooling the plate and producing increased local stresses. To investigate the effect this would have on the coating, a sample of the coated Inconel was heated in a laboratory furnace to 2000°F. The sample was then removed from the furnace and immediately submersed in a glass of cold tap water. Visually, no effects on the coating or the metal could be observed. The sample was sent to ORNL for further evaluation.

Figure 2.14 shows the mechanical cleaners. The mechanical rapper consists of a stainless steel pipe that can be manually rapped on the downstream (top) side of the distributor plate. The rapper is capable of dislodging loose granular deposits similar to that found in the internal extraction test.

The wire brush, shown in Figure 2.14, is a stainless steel high-temperature brush that can also mechanically dislodge the fouling material. However, it operates on the upstream (bottom) side of the distributor plate. The brush manually wipes the plate and can also remove material that has lodged in the distributor plate holes.

2.2.2.2 Test Results

- Laboratory

The fouling test unit was tested in the laboratory prior to being installed at the host site. The purpose of the laboratory testing was to shake down and calibrate the unit. A photograph of the unit installed in the laboratory is shown in Figure 2.15. Flue gas flow is simulated by the fluidized bed-burner facility on the right side of the wall. A transition duct connects the burners to the 1/10-scale fouling unit situated on the left-hand side of the wall. The hot gas is pulled through the unit by the blower and then sent to an existing exhaust system (not shown).

The temperatures, flow rates, heat losses, and pressure drops were determined during the testing. A typical test run is shown in Figure 2.16. The flow rate was 383 scfm and the plenum inlet temperature was just under 1000°F. The insulation in the unit proved to be effective. The total heat loss from the plenum inlet to the freeboard exit amounted to 1.3 percent of the total heat content of the gases. This allowed the distributor plate temperature to be close to the gas temperature; a necessity in the full-scale unit so that high effectiveness can be achieved.

The uninsulated stainless steel pipe accounted for an 8-percent heat loss. This high heat loss is desired so that a minimum of fan dilution air is required to cool the gases down to a temperature acceptable to the fan. In this test the dilution air cooled the gases down to 455°F, well below the fan upper temperature limit.

The pressure drops across the distributor plate and orifice were 3.5-in. wc and 1-in. wc, respectively. The pressure rise across the fan to make up for this is a maximum of 12-1/2-in. wc. Most of the remainder of the fan pressure rise was taken up in the damper to control the flow rate and the balance in the piping and ducting.

Figure 2.15 Photograph of Fouling Test Unit Installed in Laboratory

Figure 2.16 Laboratory Test Run

Shakedown of the unit was satisfactorily completed during the laboratory testing. The control system was tuned to give the desired response and all subsystems were made operational.

- Field

The test unit was installed in VMC's plant sidestream to furnace No. 2. A photograph of this arrangement is shown in Figure 2.17. Ten percent of the flue gases are pulled by the blower through a 1-ft² opening in the flue, and through the distributor plate. The gases are then returned to the top of the flue. Currently, the unit has been operating continuously for 170 hours with no evidence of fouling. However, a continuous run of over 2000 hours will be conducted before any conclusions about fouling can be made. A schematic of a typical test run is shown in Figure 2.18. Heat losses from the unit were 3.3 percent from the plenum-freeboard and 21 percent from the stainless steel pipe as desired.

2.2.2.3 Fouling Unit Test Plan

The test plan for the fouling, corrosion, and life tests is shown in Figure 2.19. The unit will operate for about 2000 hours at the design temperature and flow rate. Beyond 2000 hours, the unit will operate at a reduced temperature to both simulate media temperature gradients existing in the full-scale unit and to observe the effects of reduced operating temperature on the unit's performance. Initially, no media will be used. The alumina media will be added to the unit after a few weeks of testing.

Both daily and weekly inspections will be used to determine plate fouling and corrosion tendencies. For the daily inspections, an employee of VMC will record and telephone to Thermo Electron the status of all read-out devices. Any pressure buildup or flow rate reduction, indicative of fouling, will be determined. A more detailed examination will be conducted weekly by either Thermo Electron employees or the local engineers. At

Figure 2.17 One-Tenth Scale Fouling Unit Installed Sidestream to VMC's No. 2 Furnace

Figure 2.18

Figure 2.19 Fouling Unit Test Plan

that time, the unit will be partially disassembled and a close examination of the distributor plate will be made. Fouling, as evidenced by material buildup on the plate or in the holes, not discernible from the readout devices, will then be uncovered as well as distributor plate corrosion problems.

The assumption that no fouling problems will occur is unrealistic. Fouling is anticipated and steps will be taken to minimize or eliminate its impact. First, when fouling occurs samples of the fouling material will be obtained. This will be sent to ORNL for chemical and physical analysis. This will yield information that will aid in selecting the optimum cleaning technique. Second, the cleaning techniques described in Section 2.1.2.1 will be tested. Based on the results of these tests, the best cleaning technique will be identified.

Coupon tests have indicated that the plate will corrode at a slow rate. If, however, the corrosion rate is unacceptably rapid a second identical coated Inconel plate will be available to allow the tests to continue. However, this would indicate that the life of the current distributor plate is unacceptably short. Therefore, a plate of an alternate alloy or coating will be selected and installed in the unit. The alternate material will be selected from a combination of metals and coatings coupon tested at the same time as the fouling unit testing is being conducted. These tests are described in Section 2.1.2.

At the conclusion of the fouling unit testing, the distributor plate will be analyzed to determine whether any mechanical property changes occurred due to its exposure and to ascertain its expected overall life.

The testing described in this chapter will determine the fouling and corrosion tendencies, and the life of the distributor plate. In addition, this testing will identify the optimum alloy-coating system and the cleaning technique necessary to assure acceptable distributor plate operation and life. This will substantially reduce the risks involved in installing a full-scale fluidized bed recuperator.

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3. LABORATORY TESTING ON THE INTEGRATED FLUIDIZED BED

Laboratory testing of the integrated FBWHR system will be performed prior to building a full-scale unit so that overall and component performance can be optimized. In particular, the following two objectives will be addressed:

- 1) Integrated performance development and documentation - The performance of the integrated system which includes two fluidized beds, particle lift line, and associated hardware will be tested and documented over the complete operating range of the system. The system will be modified as necessary to optimize the performance.
- 2) Component Final Development - Individual components, such as the L-valve, have already undergone preliminary testing in the laboratory. The final testing and development of these components will now be conducted.

3.1 SYSTEM DESCRIPTION

A schematic of the laboratory test unit is shown in Figure 3.1. The unit consists of a hot side fluidized bed (8 ft x 6 ft x 2 ft) mounted above a cold side fluidized bed (6 ft x 4 ft x 1-1/2 ft), a particle circulatory system, a furnace simulator, a combustion air blower, and an exhaust system. The furnace simulator produces high-temperature, clean gas that simulates the temperature, flow rate, and pressure of an aluminum smelting furnace flue. The hot gas passes through the upper fluidized bed, heating the particles, and is then discharged to the atmosphere by the exhaust system. In the lower fluidized bed a combustion air blower pushes air through the lower distributor plate. The air is heated by the hot particles moving across the lower bed.

The particle circulatory system consists of two L-valves, one feeding particles into the lower bed and one into the upper bed. A pneumatic

Figure 3.1 Laboratory Test Facility

lift line carries the particles from the lower to the upper bed. Since the particles entering the lift line from the combustion air heat exchanger are hotter than the lift line air, the lift line also acts as a heat exchanger. This preheated air is then brought into the plenum of the lower fluidized bed where it mixes with the balance of the combustion air from the blower.

Associated controls and instrumentation will be provided to allow control and documentation of the units' performance.

3.2 PERFORMANCE ANALYSIS

To determine the preheat capabilities of the FBWHR system, an analysis of the heat transfer process was performed. Each component was modelled individually and then assembled together to yield a set of simultaneous linear equations. The solution of these equations gives the performance. The following is a brief outline of the analysis.

3.2.1 Fluidized Bed

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.

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 backmixing of the particles is modelled as an effective thermal conductivity, an energy balance on a differential element, shown in Figure 3.2, within the bed

Figure 3.2 Temperature Profile Model :

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

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.

This equation was solved using appropriate boundary conditions to give the temperature profile. A family of curves is shown in Figure 3.3 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. Figure 3.4 is a comparison of theoretical and measured temperature profiles showing excellent agreement. 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. This is illustrated in Figure 3.5.

3.2.2 Lift Line

In the lift line, both the gas and the particles are travelling in the same direction, thus it can be modelled as a parallel flow heat exchanger. The effectiveness of a parallel flow heat exchanger is:

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Figure 3.3 Calculated Temperature Profile in Fluidized Bed

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Figure 3.4 Experimental Temperature Profile Compared to Theory

Figure 3.5 Conductivity of Fluidized Bed as a Function of Gas Velocity

$$\epsilon = 1 - \exp \frac{[-N(1+C)]}{1+C}$$

where N is the number of transfer units and C is the thermal capacity ratio. It can be shown that the number of transfer units, N , can be expressed as:

$$N = \frac{6 h t}{\rho C_p d_p}$$

where h is the heat transfer coefficient, t is the residence time, ρ is the particle density, C_p is specific heat capacity, and d_p is the diameter of the particles. The value of N should be as high as possible but cannot be determined analytically. However, it is expected that N will be between 1.0 and 2.7. Figure 3.6 shows a comparison of the effectiveness of a fluidized bed and the lift line. It can be seen that a significant amount of heat is transferred in the lift line.

3.2.3 Integrated Performance

The design and off-design performance characteristics of the integrated system are shown in Figures 3.7 and 3.8, respectively. In Figure 3.7 the simulated flue gas is at 2000°F and the unit produces a preheat combustion air temperature of 1000°F. In the off-design condition, when the furnace flow rate is reduced by a factor of two and the flue gas temperature is 1400°F, the preheated combustion air temperature is 700°F.

In both of these cases, the lift air was returned to the combustion air fluidized bed. If this is not done the preheat temperature decreases by 50° to 100°F, depending on the exact conditions. Figure 3.9 compares the performance of the FBWHR system with and without the return of the lift air under various conditions. It can be seen that the return increases the overall effectiveness by 5 to 7 percent.

Figure 3.6 Thermal Performance of Lift Line Heat Exchanger

Figure 3.7 Performance of FBWHR System Under Design Conditions

Figure 3.8 Performance of FBWHR System at Turndown

Figure 3.9 Performance of FBWHRs with Return of Lift Line Air

3.3 TEST PLAN

Testing of the FBWHR system will consist of three major tasks: 1) L-valve testing, 2) particle circulatory testing, and 3) complete integration testing.

Figure 3.10 is a schematic of the test apparatus that will be used for the circulatory system tests. The purposes of these tests will be to determine the limits of operation of the lift line and to develop proper controls for the feed system.

The fact that the lift line operates as a heat exchanger complicates the problems of designing the lift system. The air is heated as it contacts the particles expanding and increasing in velocity. The pressure drop therefore increases requiring more energy for the lifting process.

The test facility will allow the accurate determination of the optimum control mechanisms and operating regimes of the L-valve and lift systems.

Once the lift line and feed systems are developed they will be incorporated into the fluidized beds as shown in Figure 3.1 and the complete circulatory system will be tested. This test will integrate all components and allow development of a circulatory system which will maintain a steady continuous circulation of particles.

The burner will then be turned on to test the thermal performance of the system. These tests will include performance at design and off design points. An additional result of these tests will be the determination of the performance of the lift line heat exchanger.

Figure 3.10 L-Valve Feed Control Test System and Lift Line

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4. SUMMARY AND FUTURE WORK PLAN

During this reporting period work has been initiated towards solving the two remaining technical concerns. The first of these, distributor plate fouling and corrosion, is being addressed by conducting field testing of a scaled hot stage fluidized bed and expanding the material coupon exposure tests. Initial tests from the scaled unit and continuing tests from the coupon exposure show promising results. The second problem, that of integrating the dual fluidized-bed concept and completing the sub-system development, is being addressed by modifying the existing laboratory facility so that a dual fluidized-bed system can be tested.

Over the next six months efforts will focus on continuing the field testing and constructing the laboratory facility.