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FLUIDIZED-BED WASTE-HEAT RECOVERY SYSTEM
DEVELOPMENT

Semiannual Report, February 1—July 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 preceding 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, -2, and -3, include:

- Fabrication, laboratory testing, and field installation of a fluidized-bed fouling and corrosion test unit including several alternate distributor plate cleaning systems;
- Continued coupon testing of aluminum-diffusion-coated Inconel 625 in Vulcan Materials Company's (VMC) flue and procurement of alternate distributor plate alloys and coatings;
- Design of a laboratory test facility for FBWHR system integrated testing;
- Characterization of furnace operations; and

- Analytical development and experimental verification of the distributor plate stability criteria, fluidization characterization, and heat transfer characteristics.

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

- Field testing of a one-tenth-scale fluidized-bed fouling and corrosion test unit;
- Testing of distributor plate cleaning systems capable of overcoming the fouling process;
- Expanded coupon testing of several distributor plate alloy-coating systems in VMC's No. 2 flue. This will determine the optimum alloy-coating combination; and
- Fabrication of the laboratory test facility in which integrated fluidized-bed testing and subsystem development will be completed.

In conclusion, the FBWHR system fulfills a real need: waste-heat recovery from high-temperature, dirty, corrosive furnace exhaust gases. This program is developing the technology to build the system.

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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/yr,* 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 system 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

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 is 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 purchasers. 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.

VMC will host the field testing of the FBWHR system. VMC is the country's third largest secondary producer of aluminum, tin, zinc, and

*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

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 field testing and laboratory facility fabrication. Specifically:

- The field test unit, designed to address the remaining problems of distributor plate fouling, corrosion, and stress rupture life, was field tested. During this testing, the distributor plate fouling was characterized and various cleaning systems were tested.
- Expanded coupon testing, including several alloy-coating systems, was conducted.
- Fabrication of the laboratory test facility was completed. Integrated fluidized-bed testing and subsystem development will be conducted in this facility.

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. UPPER DISTRIBUTOR PLATE MATERIALS TESTING

There are currently two major concerns in the design of the FBWHR system — the upper distributor plate fouling and materials selection. Several scaled field tests were conducted to determine the extent of each of these concerns. In this chapter the basis of the materials selection concern is reviewed and results of the tests conducted to date are presented. In Chapter 3, the upper distributor plate fouling test results will be presented.

2.1 BACKGROUND

2.1.1 Material Description

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-inch holes spaced on 1/4-inch 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 because of 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 coating on the Inconel 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.

Other alloy-coating systems that offer specific advantages over the aluminum-diffusion-coated Inconel, such as improved strength or corrosion resistance, are also being tested. Table 2.1 is a list of these metals and coatings.

2.1.2 Previous Test Results

- Material Temperature Measurements

The alloys listed in Table 2.1 were immersed in VMC's No. 2 furnace flue for exposure testing. Coupon temperature measurements were taken during the testing with thermocouples welded to each coupon.

Because corrosion is a strong function of temperature, it is necessary to maintain the coupon temperatures at about the same temperature as the fluidized-bed distributor plate. In a well-insulated unit, the distributor plate is 100° to 200°F lower than the fluidized bed. Figure 2.1 shows the measured coupon temperature (solid line) and the flue gas temperature (dashed line) as a function of time. The coupon temperature is about 50°F lower than the flue gas temperature or about 50° to 150°F higher than the distributor plate temperature. Hence, the coupon tests yield slightly conservative corrosion rates.

- Material Exposure Test Results

The exposed material samples were examined by first cutting off a small piece of the material and then taking photomicrographs of the cut piece. The photomicrograph for the aluminum-diffusion-coated Inconel 625, exposed for 911 hours, is shown in Figure 2.2. For comparison, a

TABLE 2.1
COUPON TESTING PLAN

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

Figure 2.1 Material Sample and Flue Gas Temperature

Worst: Approximately 50% Life Used

Average: Approximately 30% Life Used

Best: Approximately 20% Life Used

Figure 2.2 Photomicrographs of Exposed Coated Inconel

photomicrograph of an unexposed sample is shown in Figure 2.3. The top micrograph in Figure 2.2 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. No damage to the substrate material occurred.

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 2.4. The coating was mostly protective, although a small amount of corrosion (about 0.0065-inch deep) had occurred on the substrate. The design distributor plate thickness is 0.125 inch therefore the damage represents a 5-percent reduction in thickness.

The coated Inconel sample can be compared to the uncoated exposed Inconel sample. A photomicrograph is shown in Figure 2.5. The corrosion depth on the uncoated sample was about 0.03 inch – an increase in damage over the coated sample by a factor of 4-1/2.

2.2 CURRENT TEST RESULTS

The testing discussed in the previous section was continued during this reporting period, along with exposure testing of the materials listed in Table 2.1. The most recent results are discussed in this section.

2.2.1 Coated Alloy – Recent Exposure Test Results

The coated alloy coupon samples have between 750 to 5650 hours of exposure time in VMC's No. 2 flue, as shown in Table 2.2. A summary of the number of exposed hours each sample had when removed from the flue for analysis is given in Table 2.3. All the coated alloy samples listed in Table 2.2 are currently continuing exposure testing.

Photomicrographs of the coated Inconel 625 samples with 911 and 2250 hours of exposure were shown in the last section. Photomicrographs at 3200 and 4000 hours of exposure are presented here. Figure 2.6 shows the photomicrographs of the 3200 hours exposed sample.

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Figure 2.3 Photomicrograph of Unexposed Coated Inconel

Figure 2.4 Photomicrographs of Exposed Coated Inconel 625 (2250 Hours)

Figure 2.5 Uncoated Inconel 625 Exposed for 2250 Hours

TABLE 2.2
MATERIAL COUPON SAMPLES

Coating	Alloy	Perforated	Exposure Time as of 7/31/83 (hr)
Coated Alloys			
Coatings Technology	Inconel 625	Yes	5650
Alon	Inconel 625	Yes	1200
Alon	Haynes 188	No	1200
Alon	316 SS	No	1200
Alon	Inconel 601	No	1200
Refractory Corporation	Inconel 625	Yes	750
Refractory Corporation	316 SS	No	750
Aremco	Inconel 625	Yes	750
Aremco	316 SS	No	750
None	Cabot 214	Yes	1200
Ceramics			
	Silicon Carbide	No	8000*
	Alumina	No	4000*

*Samples permanently removed.

TABLE 2.3
COATED ALLOY MATERIAL EXPOSURE SAMPLES
REMOVED FOR INSPECTION

Coating	Alloy	Exposure Time When Retrieved for Analysis (hr)	Analyzed?
Coatings Technology	Inconel 625	911	Yes
Coatings Technology	Inconel 625	2250	Yes
Coatings Technology	Inconel 625	3200	Yes
Coatings Technology	Inconel 625	4000	Yes
	Cabot 214	1200	Pending
Alon	Haynes 188	1200	Pending
Alon	Inconel 601	1200	Pending

 Current
Reporting
Period

Figure 2.6 Coated Inconel 625 Exposed for 3200 Hours

Attack has occurred on one side of the sample only. The damage has progressed through about one half of the sample, or about 1/32 inch. The reason for the damage on one side of the sample and not the other side is unknown. Other photomicrographs of the different areas of the same material specimen show different amounts of grain boundary attack. In some instances, the attack has gone through the entire thickness of about 1/16 inch. Possibly the coating is more protective in some areas than in others.

The damage to the sample may not be due solely to high-temperature corrosion. In addition to the 3200 hours of exposure during furnace operation, this sample was also in the flue for 2000 hours when the furnace was not operating. During this period, the temperature of the sample was ambient which could have led to condensation of water vapor onto the sample surface. This water may contain hydrochloric acid or other corrosive constituents that could damage the sample, leading to an artificial increase in the corrosion rate.

A photomicrograph of the coated Inconel sample after 4000 hours of exposure is shown in Figure 2.7. In this specimen, damage occurred equally on each side to a depth of about 0.02 inch.

A summary of the corrosion depth of the Inconel 625 (with the Coatings Technology, Inc., coating) that occurred to the samples retrieved at 911, 2250, 3200, and 4000 hours is shown in Figure 2.8. For the first 911 hours, no corrosion to the substrate material occurred. Between 911 and 2250 hours the Inconel was damaged through 0.006 inch of its thickness. This damage continued as the test progressed. At 3200 hours the damage was between 0.03 and 0.06 inch (the entire sample thickness). At 4000 hours photomicrographs show the damage to be about 0.04 inch. The damage increases with time with a considerable amount of scatter in the data at 3200 hours.

Figure 2.7 Coated Inconel 625 Exposed for 4000 Hours

Figure 2.8 Corrosion History of Inconel 625 Exposed in Flue

For comparison, the corrosion rate of uncoated Inconel is also shown in Figure 2.8. At 2250 hours the uncoated Inconel's corrosion is about 4-1/2 times greater than that of the coated Inconel. At 3200 hours the corrosion of the uncoated Inconel is within the data scatter of the coated Inconel.

From the foregoing results, it is possible to specify the distributor plate's original thickness needed to allow a plate life of one year using the coated Inconel. The following assumptions are made:

- Grain boundary attack reduces the plate's effective thickness by the depth of the attack. Hence, grain boundary damage to 0.02 inch of the plate would reduce the effective thickness by 0.02 inch.
- The minimum effective thickness required to support the plate stress is 1/8 inch.
- Grain boundary damage is linear with time. From the preceding test results, a conservative estimate for this damage is 3×10^{-5} in./hr after the first 1000 hours.

Based on the above, the distributor plate's original thickness must be about 0.35 inch so that, at the end of one year, the remaining effective thickness would be greater than 1/8 inch.

It should be noted that the above estimate is conservative:

- Coupon corrosion rates are accelerated because they are being tested at temperatures higher than design. Figure 2.1 shows the coupon sample temperature to be 50°F lower than the flue gas temperature, while the design value is 100° to 200°F below the flue gas temperature.
- The optimum alloy-coating system has not yet been identified. An improvement in the corrosion resistance of either the alloy or coating is possible, which would lead to a prediction of improved distributor plate life.

Samples of Cabot Alloy 214, Haynes 188 with an Alon coating, and Inconel 601 with an Alon coating were removed after 1200 hours of exposure. An analysis of these samples is currently underway.

2.2.2 Ceramic Exposure Test Results

Both silicon carbide and alumina were exposed in the flue; the silicon carbide for 8000 hours and the alumina for 4000 hours. A photomicrograph of the silicon carbide is shown in Figure 2.9. No corrosion can be observed. A thin slag layer is, however, present on the surface. The alumina also showed no corrosion damage, however, significant cracking was present. This is expected because of the poor thermal shock properties of alumina.

2.3 MATERIAL EXPOSURE TEST CONCLUSIONS

The following conclusions can be drawn from the preceding test results:

- Coated alloys are viable materials for use as distributor plates.
- Aluminum-diffusion-coated Inconel 625 must be 0.35-inch thick for a one-year life.
- Silicon carbide corrosion resistance is unexcelled. However, it is not commercially available.
- Alumina's susceptibility to thermal shock cracking eliminates it as a distributor plate material.

Figure 2.9 Silicon Carbide Exposed to Host Furnace Flue Gases for
~8000 Hours

3. UPPER DISTRIBUTOR PLATE FOULING

One concern with the FBWHR system is the possible deposition (or condensing) of particulate matter on the hot distributor plate. This material builds up around the plate holes, increasing the pressure loss and reducing the gas flow rate. 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, small-scale experiments were conducted in this program to investigate the susceptibility of distributor plate fouling. The experiments indicated that fouling was of immediate concern. Accordingly, a 1/10-scale fouling unit was built to explicitly determine the fouling characteristics of distributor plates and the effect of plate cleaning systems. A description of that fouling unit was given in the previous semiannual report (report number DOE/ID/12302-3). A description of the test results obtained in this reporting period is given in this chapter.

3.1 FOULING TEST UNIT CHARACTERIZATION

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 smelters. The specific objectives of the field tests are to determine the:

- Distributor plate fouling characteristics;
- Optimum distributor plate cleaning techniques;
- Distributor plate corrosion tendencies;
- Distributor plate life; and
- Optimum distributor plate material.

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 techniques will be used to clean the distributor plate and the most effective cleaning method determined.

2. Monitoring the distributor plate stress rupture life and corrosive characteristics. If either is beyond acceptable limits, alternate distributor plate materials will be tested.

The test unit was installed in VMC's plant, sidestream to furnace No. 2. Figure 3.1 is a schematic of this arrangement. A photograph of the installed unit is shown in Figure 3.2. Ten percent of the flue gases are pulled by the blower through a 1-ft² opening in the flue, and then through the distributor plate. The gases are then returned to the top of the flue.

Design conditions for the unit are given in Table 3.1. Temperatures, pressures, and flow rates, recorded during a typical test run, are shown in Figure 3.3. The flue gases exit the flue at 2020°F and enter the plenum at 1900°F. Heat losses in the plenum and freeboard amount to 3.3 percent of the total flue gas heat content resulting in the flue gas exiting the freeboard at 1840°F. The distributor plate temperature of 1820°F is close to that of the gas temperature. Heat losses in the uninsulated duct are designed to be high, at 21 percent, so as to minimize the required dilution air into the fan. The total flue gas flow rate through the unit is 270 scfm, resulting in a distributor plate pressure drop of 5.5 in. wc and an orifice pressure drop of 7 in. wc.

A plot of the distributor plate temperature as compared to the flue gas temperature during a 24-hour period is shown in Figure 3.4. The plate temperature is typically 100° to 200°F below the flue gas temperature.

3.2 FOULING TEST RESULTS

The fouling test unit was operated for a total of 1000 hours during this reporting period. During that time four fouling tests were conducted,

Figure 3.1 Fouling Test Unit

Figure 3.2 One-Tenth Scale Fouling Unit Installed Sidestream to VMC's No. 2 Furnace

TABLE 3.1
ONE-TENTH-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

Figure 3.3

Figure 3.4 Distributor Plate and Flue Gas Temperature in Fouling Test Unit

as depicted in Figure 3.5. The objective of the first, second, and fourth tests was to characterize the distributor plate fouling in terms of both identifying the fouling constituents and evaluating the time required to foul. In addition, the first test evaluated off-line cleaning systems. The second and third test runs were conducted to evaluate the on-line cleaning systems.

3.2.1 The Distributor Plate ΔP

Distributor plate fouling can be identified by observing the distributor plate pressure drop. Because the flow rate is automatically held fixed by the damper control system, a decrease in the distributor plate open area, due to hole fouling, results in an increase in distributor plate pressure drop. This is shown by the governing flow equation:

$$\dot{m} = C A \sqrt{\Delta P}$$

where:

$\dot{m}$ = flow rate

P = distributor plate pressure drop

C = constant.

For a fixed $\dot{m}$, a decrease in A results in an increase in ΔP .

If the distributor plate ΔP continued to increase, the blower capability would eventually be exceeded (22 in. wc). Additional fouling would thus also decrease the flow rate. If fouling continued unabated, the distributor plate would become completely plugged resulting in zero flow rate and a distributor plate ΔP equal to the blower's maximum capability.

The distributor plate fouling and orifice ΔP for a typical test run are shown in Figure 3.6. For the first 60 hours, the distributor plate ΔP increases continuously. After 60 hours, the continuing fouling results in a total system pressure drop greater than the blower's capability, hence the flow rate (orifice ΔP) decreases. After about 160 hours the

Figure 3.5 Field Test Unit Experience

Figure 3.6 Distributor Plate Fouling Characteristics - Test 2

distributor plate is completely plugged, as evidenced by zero flow rate and a distributor plate ΔP greater than 20 in. wc.

The flue gas and plenum gas temperatures during this test are shown in Figure 3.7. The plenum gas temperature is close to the flue gas temperature until the flow rate begins to decrease (beyond 60 hours). As the flow rate continues to decrease, the temperature difference between the plenum gas and flue gas increases. At 160 hours fouling is complete, there is little gas flow, and the temperature difference is large.

3.2.2 Fouling Constituent Characterization

During tests 1 and 2, the distributor plate was allowed to foul completely, resulting in the complete plugging of the distributor plate. The unit was then partially disassembled and samples of the fouling material were taken. The samples were sent to Oak Ridge National Laboratories and Herron Testing Laboratories, Inc., Cleveland, Ohio, for an X-ray diffraction scan and a spark source mass spectroscopy analysis. The results are given in Table 3.2.

The major deposit constituents in test 1 is aluminum and in test 2, magnesium. Each can be traced to the chlorinating process. In test 1, aluminum is probably a result of the chlorine combining with aluminum, volatilizing, and then reacting with water to form Al_2O_3 . In the second test, magnesium probably forms from entrained $MgCl$, which also reacts with water to form MgO . The source of the other constituents in each test run can be traced to the fluxes added to the melt, such as sodium and potassium, and the remaining constituents can be traced to either the melt itself or the furnace wall material.

3.2.3 Effect of Temperature on Fouling

Temperature can affect fouling because at high temperatures low vapor pressure flue gas constituents are unable to condense on the distributor plate or if already condensed, would vaporize off the plate.

Figure 3.7 Foulings Test Unit Temperature - Test 2

TABLE 3.2
DEPOSIT ANALYSIS

Material	Deposit from Test		Assumed Compound	Possible Source
	Run No. 1	Run No. 2		
Aluminum	Major	Minor	Al_2O_3	Volatilized AlCL
Magnesium	1%	Major	MgO^*	Entrained MgCL
Iron	Minor	2%	Fe_2O_3	Duct Corrosion
Sodium	2%	Minor	NaCL^*	Flux
Calcium	1%	4%	$\text{CA}(\text{ClO}_4)_2^*$	Refractory
Potassium	1%	2%	KCL^*	Flux
Silicon	0.3%	2%	SiO_2	Alloying Material
Chromium	0.8%	2%	CrO	
Zirconia	0.4%	2%	ZrO_2	

*Indicates Water Soluble

As an example, KCl , CaSO_4 , and NaCl fluxes vaporize between 1400° and 2600°F . If these are binders holding the deposit, then heating to this range will also remove the deposit.

The temperature effect on fouling was verified by observing the plate ΔP and the flue gas temperature during a 10-hour period, as shown in Figure 3.8. The ΔP changed at the same time as the flue gas temperature did and in the opposite direction. Between 4 and 5 hours the temperature increased from 700° to 1900°F . At the same time, the plate ΔP decreased from 10 in. wc to 5 in. wc, presumably because the fouling particulates vaporized off the plate. Conversely, when the temperature decreased the ΔP increased. From 5 to 8 hours the flue gas temperature dropped back to 700°F and the plate pressure drop increased to 15 in. wc, presumably because flue gas constituents were able to condense on the plate.

This test suggests that fouling can be delayed by stopping the blower whenever the flue gas temperature goes below 1000°F , thus avoiding the condensing part of the observed cycle. This, however, would not eliminate fouling because some flue gas constituents condense at temperatures above the maximum flue gas temperature.

3.2.4 Effect of the Chlorinating System on Fouling

The previously mentioned fouling tests were conducted while VMC was using a continuous chlorinating system that is a relatively new design. In this design, chlorine is injected into the batch continuously during the charging cycle, as contrasted to the conventional system in which the chlorinating is done during a holding period at the completion of the charging cycle. The continuous chlorinating system eliminates this holding period, decreasing the total furnace fuel consumption. Because of this fuel savings, it is expected that trends in the industry are to the continuous chlorinating system. Hence, these fouling test results are representative of what would be expected in any furnace. However, due

Figure 3.8 Time Variation of Fouling Characteristics

to the recent introduction of this system, one question is how sensitive the fouling phenomenon is to the chlorinating system.

Fortunately, VMC switched from continuous to batch chlorinating on the No. 2 furnace for about two months. During that time, test 4 was conducted in which no on-line cleaning was used. The purpose of this test was to compare the fouling characteristics with the batch chlorinating system in place to those obtained in tests 1 and 2, where the continuous system was used.

The results of test 4 were:

- The distributor plate fouled completely. The appearance of the fouled plate and the fouling material was identical to that of the previous fouling test results.
- The time for the fouling to occur was 350 hours (Figure 3.5). This is of the same order as tests 1 and 2 (125 to 350 hours).

The fouling material for this run was sampled and will be analyzed and compared to the previous samples.

These preliminary results indicate that fouling will occur and is only secondarily dependent upon the chlorinating system.

3.2.5 Cleaning System Effect on Fouling

Several methods were tested to clean the distributor plate while the unit was off-line* and also on-line. A summary of the methods used off-line is shown in Table 3.3. The air lance, steam, and water wash were all effective in cleaning the plate. In the case of the water wash and steam cleaning, water soluble constituents of the fouling deposit, such as MgO , NaCl , KCl , and $\text{Ca}(\text{ClO}_4)_2$, are easily washed away.

*No flue gases flowing through the test unit.

TABLE 3.3
ALTERNATIVE CLEANING TECHNIQUES

Air Lance	Removes Deposit Continuous Use Inhibits Fouling
Moderate Pressure Steam	Removes Deposit
Water Wash	Removes Deposit
Mechanical Rapper	No Effect
Wire Brush	No Effect

The wire brush and the mechanical rapper were not effective in cleaning the plate off-line.

The air lance was also used on-line to prevent the plate from fouling during operation. The air lance was used once a day for about a 3-minute duration. The flow rate through the air lance was less than 0.01 percent of the total flue gas flow rate through the test unit resulting in a negligible gas temperature drop. The effect of the air lance on plate ΔP is shown in Figure 3.9. While the distributor plate ΔP increases each day its trend is reversed by the air lance so that the ΔP never gets much above the design value during the entire 80-hour test. For instance, from 21 to 25 hours the ΔP increases from 6 in. wc to 7.6 in. wc. The air lance is then used and the ΔP decreases back down to 6 in. wc. This can be compared to the tests without on-line cleaning, Figure 3.6, where, during the same time span, the ΔP increases by a factor of 2 over the design value.

The plenum gas and flue gas temperatures during the air lance cleaning are shown in Figure 3.10. The plenum gas temperature never gets much below the flue gas temperature confirming the air lance's effectiveness.

3.3 CONCLUSIONS

The following conclusions can be drawn from the preceding data:

- Fouling is a concern whenever recuperators are used in the secondary aluminum smelting furnaces.
- The source of the fouling constituents can be traced to the chlorinating and fluxing process, or from entrained material.
- The time for complete distributor plate fouling to occur is about 150 to 350 hours.
- At least some, if not most, of the fouling material is water soluble.
- Automatic cleaning systems can be used to keep the distributor plate clean.
- Temperature excursions can be used to mitigate fouling.

Figure 3.9 Distributor Plate Pressure Loss - Test 3

Figure 3.10 Fouling Test Unit Temperatures - Test 3

4. LABORATORY TESTING OF THE INTEGRATED FLUIDIZED BED

4.1 BACKGROUND

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, a 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.

4.1.1 System Description

An isometric drawing of the laboratory test unit is shown in Figure 4.1. The unit consists of a hot side fluidized bed (outside dimensions 8 ft x 6 ft x 2 ft) mounted above a cold side fluidized bed (6 ft x 4 ft x 1½ ft), a particle circulating 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.

Figure 4.1 Laboratory Test Facility

The particle circulatory system consists of two L-valves, one feeding particles into the lower bed and one into the upper bed. A pneumatic lift line carries the particles from the lower to the upper bed. Because 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 unit's performance.

4.1.2 Performance Analysis

To determine the preheat capabilities of the FBWHR system, an analysis of the heat transfer process was performed. Each component was modeled 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.

- Fluidized Bed

A fluidized bed can be modeled 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 modeled as an effective thermal conductivity, an energy balance on a differential element, shown in Figure 4.2, within the bed

Figure 4.2 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 4.3 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 4.4 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 0 at minimum fluidization to over 5000 Btu/hr-ft-°F at 10 ft/sec. This is illustrated in Figure 4.5.

● Lift Line

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

Figure 4.3 Calculated Temperature Profile in Fluidized Bed

Figure 4.4 Experimental Temperature Profile Compared to Theory

Figure 4.5 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 4.6 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.

● Integrated Performance

The design and off-design performance characteristics of the integrated system are shown in Figures 4.7 and 4.8, respectively. In Figure 4.7, 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 2 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 were not done, the preheat temperature decreased by 130° to 160°F, depending on the exact conditions.

4.2 FACILITY FABRICATION

Fabrication of the facility was completed during this reporting period. Specific accomplishments included:

Figure 4.6 Thermal Performance of Lift Line Heat Exchanger

Figure 4.7 Performance of FBWHR System Under Design Conditions

Figure 4.8 Performance of FBWHR System at Turndown

1. Fabrication and installation of the upper fluidized bed;
2. Fabrication and installation of the particle circulatory system, which includes L-valves, lift line, rotary feeder, downcomer, and control systems;
3. Installation of the burner systems, including air line, gas line, control valves, and controllers;
4. Installation of exhaust system; and
5. Installation of instrumentation.

4.3 CURRENT TEST RESULTS

Two sets of component development and shakedown tests were conducted during this reporting period:

- L-valve feed and control and sealing tests; and
- Particle lift line tests.

The results of these tests are reported in this section.

4.3.1 L-Valve Feed Control and Sealing

Figure 4.9 is a schematic of the particle circulatory system and system pressures. The circulation rate of the alumina particles is controlled by a rotary feeder feeding into the upper fluidized bed. The particle flow rate into the lower fluidized bed and into the lift line must match this rate exactly. The feed mechanism must also seal against the leakage of air from the lift line into the lower fluidized bed and between the two beds. A high leakage rate between various components will decrease the system performance and, in extreme cases, stop the circulation of the particles rendering the system ineffective.

To accomplish this sealing, one L-valve is used between the two beds, one L-valve is used between the lower bed and lift line, and a rotary feeder is used between the upper lift line and upper bed. The L-valves must seal against pressures of 21 and 22 in. wc. In an L-valve,

Figure 4.9 Particle Circulatory System

the sealing is accomplished by a packed bed inventory of alumina in a standpipe. The leakage of air can be calculated from the Ergun equation:

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

For a maximum leakage velocity of 0.5 ft/sec and a pressure difference of 21 in. wc, a packed bed 2.2 feet in height is required. Tests of the sealing of a packed bed were performed in the previous phase of this program.

While being able to seal against a pressure difference, the L-valve must also allow the solids to flow through. This can be accomplished by injecting air (aeration) into the bottom of the L-valve to push the particles out of the bottom. The flow rate of particles out of the L-valve increases with the amount of aeration above a minimum aeration rate. Figure 4.10 shows some typical experimental data taken from tests performed previously in this program.

To control the flow rate of particles through the L-valve, the aeration flow is adjusted. A pressure switch is used to sense the level of the inventory in the standpipe. The pressure difference increases with inventory height. When the inventory rises above a specified height, the aeration flow is turned on. When it falls below a different height, the aeration flow is turned off. This on-off system, illustrated in Figure 4.11, causes a pulsatile flow of particles out of the L-valve. Occasionally this pulsatile flow causes particle surges that lead to lift line choking. The pulsatile flow also causes large fluctuations in the lift line flow.

To solve this problem, a high-low control system was developed. In this system, the aeration flow varies between a high and low flow rate and is not completely shut off. This system is shown in Figure 4.12. The high-low controller minimizes both the surge of solids and the fluctuations

Figure 4.10 Performance of an L-Valve

Figure 4.11 L-Valve On-Off Feed Control System

Figure 4.12 L-Valve High-Low Feed Control System

of the lift line air flow. Figure 4.13 illustrates the operating characteristics of the two controllers. Although the average solids flow and lift line air flow are the same for both systems, the fluctuations in the high-low control are much lower.

4.3.2 Lift Line Testing

- Theory

In the design of industrial vertical pneumatic conveying systems, choosing the correct velocity at which to transport the solids is critical. Too low a velocity will result in an unacceptable, unstable, slugging flow (choking); too high a velocity will result in excessive gas requirements and high pressure losses. The general relationship between velocity and pressure drop per unit length ($\Delta P/L$), in a dilute-phase vertical riser, is shown schematically in Figure 4.14. When no solids are in the lift line, there is the familiar quadratic relationship between pressure loss and superficial velocity (curve $w = 0$). However, when solids are added to the base of the lift line, this curve is modified into the "U" shape shown in curve w_1 . At high gas velocities, the frictional resistance predominates and the pressure drop characteristic closely follows the empty tube characteristic slightly displaced by the limited particle inventory in the lift line. At low gas velocities, however, the particle inventory in the lift line is increased and provides a large static load, thereby increasing the pressure loss. This accounts for the U shape of the curve. At higher solids throughput, the characteristic curve is displaced upward and to the right, shown in Figure 4.14 as curve w_2 . Each of these curves has a minimum pressure drop, shown as point D in curve w_1 . Operation to the right of this point is stable. Operation to the left is unstable - that is, the flow will slip into choking. Choking is when the smooth flow of gas and particles breaks down into slugs with the attendant oscillating transport. Thus, two critical points are required to characterize the lift line: the choking velocity and the minimum pressure loss.

Figure 4.13 Comparison of On-Off and High-Low L-Valve Controllers

Figure 4.14 Pressure Drop-Velocity Characteristics of a Vertical Pneumatic Lift Line

- Lift Line Test Results

Experiments were performed using the apparatus shown in Figure 4.15 to determine the characteristics of the pneumatic lift line. In these tests, the particle flow rate was controlled by a rotary feeder. The particles dropped from the feeder into an L-valve. Air injected into the L-valve pushed the particles into the lift line which lifted the material a vertical distance of 22 feet into a cyclone. The lift air was vented outside and alumina was recirculated.

In the experiments, the solids flow rate was held constant and the lift velocity was varied from a maximum of 100 ft/sec to the choking limit. The pressure drop of the lift line was correlated with the lift velocity and solids flow rate. The results for five different solids flow rates are shown in Figure 4.16. The terminal velocity of the alumina particles is also shown for reference. Because small changes in the superficial velocity at this point yield large changes in the pressure drop, so much so that operation in this area is highly unstable, it is not possible to collect data at this point. The characteristics of the lift line exhibited in Figure 4.16 fit the general relationship shown in Figure 4.14 and indicate that the lift line must operate at approximately 50 ft/sec for stable operation. The lift line pressure drop at a nominal solids flow rate of 0.71 lb/sec is approximately 20 in. wc.

When the lift line is incorporated into the FBWHR system, the particles that are ejected into the lift line will be at 800°F. This will alter the lift line characteristics because the air will expand as it is heated by the particles and the kinematic viscosity will decrease. The net result will be a slight decrease in the air requirements for lifting the alumina and a negligible change in the lift line pressure drop.

Figure 4.15 Lift Line and L-Valve Feed Control Test System Configuration

Figure 4.16 Experimental Results of Lift Line Characterization

5. SUMMARY AND FUTURE WORK PLAN

During this reporting period, work has been initiated towards solving the two remaining technical concerns. The first, distributor plate fouling and corrosion, is being addressed by conducting field testing of a scaled, hot stage fluidized bed and conducting material coupon exposure testing of 10 alloy-coating systems. Test results from the scaled unit indicate that distributor plate cleaning systems will keep the plate clean indefinitely. Results from the coupon exposure tests show promising results.

The second problem, integrating the dual fluidized-bed concept and completing the subsystem development, is being addressed by a modified laboratory facility so that a dual fluidized-bed system can be tested.

Over the next 6 months, efforts will focus on continuing the field testing and conducting laboratory testing. Specifically, in the field testing:

- A long duration test will be conducted to determine the effectiveness of the air lance in cleaning the distributor plate on-line; and
- The effect of the flue gases on the alumina used for the bed media will be investigated.

In the laboratory testing:

- The complete particle circulatory system will be tested both with ambient temperature gases and the simulated hot flue gases;
- The performance of each component using the simulated flue gases will be determined; and
- The overall effectiveness of the entire system will be optimized and documented.