DOE/ID/12303-1
(DE84010358)

Energy
CONSERVATION

HIGH TEMPERATURE FLUID-BED HEAT RECOVERY FOR ALUMINUM MELTING FURNACE

Topical Report

December 1982

Work Performed Under Contract No. FC07-81ID12303

Aerojet Energy Conversion Company
Sacramento, California

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

DISCLAIMER

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A04
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication NTIS-PR-360 available from NTIS at the above address.

DOE/ID/12303-1
(DE84010358)
Distribution Category UC-95e

HIGH TEMPERATURE FLUID-BED HEAT RECOVERY FOR ALUMINUM MELTING FURNACE

December 1982

Prepared Under Department of Energy
Cooperative Agreement DE-FC07-81 ID 12303

Prepared By

Aerojet Energy Conversion Company
Sacramento, California

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 SUMMARY

The objective of the study was to establish whether technical problems would be encountered in increasing the inlet temperature of the fluid bed heat exchanger unit at Alcoa above the 1100°F target of the current contract. Specifically, the temperature range of up to, and potentially above, 1600°F were investigated to establish the benefits of higher temperature, trade offs required, and plans to achieve that technology goal.

The benefits are seen tabulated on Table 1 and are very significant, particularly at the temperature range of 1600 - 1800°F. Relative to 1100°F the heat recovery is increased by 24 - 29% at 1600 and 1800°F respectively.

TABLE 1

BENEFITS AT 1600°F TO 1800°F RELATIVE TO 1100°F

Size reduced 29 to 39% (through-flow about same)
Weight reduced 28 to 40%
Installation and acquisition costs reduced 19 to 27%
Heat recovery increased 24 to 29%
User ROI improved by about 33 to 77%
Figure of merit (heat recovery and average cost and size) factors improved 63 to 96%

An indication of the overall improvement is the return on investment perceived by a potential user who is interested in saving fuel in his operations. The improvement would be from about 33% to 77% for the respective temperature compared to 1100°F. Another figure of merit would be to take the heat recovery improvement and the average of both cost and size improvement collectively into one factor. This figure of merit would show a 63% and 96% improvement for both the respective temperatures.

As the temperature of the inlet gas is increased above approximately 1200°F, the technology problems become much tougher and the payoff is very high. The performance figure of merit nearly doubles from 1100°F to 1800°F. At the same temperature range, the fouling resistance plummets dramatically because of the stickiness of species of particles in the gas stream. Likewise corrosion resistance falls rapidly for metals that are of potential use in the heat exchanger. The creep strength of stainless steel drops off less dramatically but yet at a very rapid rate such that above 1600°F it is reduced by nearly an order of magnitude.

Each of the primary technical problems will now be discussed in turn. First, the problem of sticky particulates that would collect on the bottom side of the distributor plate and in the slot areas and being sticky would not be brushable.

The approach to the particulates problem would be to conduct laboratory tests on the types of compounds that would be resident in the particles. Additionally, potential additives to the fuel would be investigated. These include magnesia which has the potential of significantly increasing the softening temperature of many of the species of particles that are seen in the Alcoa aluminum furnace exhaust. Alternative methods of cleaning the particulates have been considered and include the use of soot blowing type equipment in combination with the brush or in place of the brush operating on the brush track. Additionally, concepts such as centrifugal force stiffened brushing have been considered good approaches to the problem.

Another problem is the thermal stresses induced in the slots due to the high temperature around the slots compared to the relatively cool temperature in the plate adjacent to the slots that is cooled by the fluid bed. Revised configurations such as lip type slot in place of the bridge slot and methods of cooling or insulating the slot itself have been considered. Cooling methods could be from the fluid bed or from either water or steam passages.

Another technology problem is due to the reduced bed area that comes from increasing temperature and therefore reducing diluent air flow. This means that the heat exchange area must be packed within the smaller bed area.

Cyclic temperature effects are a significant technology limitation and differential thermal expansion and thermal stresses must be carefully considered. A potential approach is to use new design concepts which will provide forgiving joints that have expansion compensation for expansion tolerance and consideration of methods to reduce the temperature rate of change.

Corrosion rates are an important factor with higher temperatures. As temperatures go above 1200° the corrosion rate can increase dramatically with the presence of alkalis, vanidates, and other corrosive elements. The approaches considered best are to use alternate materials including ceramics and other coatings and to keep metal temperatures down.

Alternate configurations and alternate materials for the bed support structure with the use of insulation to keep temperatures down and possibilities of cooling to keep metal temperatures down while keeping creep strength up have been considered. Support beams can be cooled in part by the fluid bed itself and can be insulated to some degree from the high temperature inlet gases.

High temperature is a problem with the brush system relative to corrosion resistance, stiffness and strength reduction. Approaches to be taken should include gravity stiffened rotating brushes off advanced materials and brushless designs.

1.0, Summary (cont.)

The bearings and trolley which support the movable brush system must use ceramics, cooling and/or insulation in the high temperature design.

The conclusions of the study are as follows:

(1) It is not feasible to plan to conduct testing at Alcoa beyond 1100°F without laboratory R&D work. The risks associated with rapid fouling by molten and sticky particulates, which would render the brush system useless, combined with rapid corrosion rates and substantially reduced creep strength are too severe.

(2) The benefits of technology advancements with higher inlet temperature capability to over 1600°F are remarkably high. For example, the user return on investment, which is the gauge of acceptability, shows an increase of between 53% and 77% at 1600 and 1800°F, respectively.

(3) Technology payoffs of this magnitude are seldom obtainable without high risk. Such is the case here; however, there are well thought out technical approaches for each potential problem area.

(4) The recommended R&D approach is therefore to complete detail analyses of the problems followed by laboratory bench-scale testing to establish technical understanding and resolution of those problems. The final step would be to retrofit the best advancements into the Alcoa test unit and test operation at gradually higher temperatures to establish the limitations and report performance.

2.0 INTRODUCTION

A shallow fluid bed waste heat recovery boiler is being developed under the DOE/Aerojet Cooperative Agreement which will be tested on an Alcoa aluminum melting furnace. The design incorporates self-cleaning to allow operation in the dirty environment.

Under the current DOE Cooperative Agreement, Aerojet will: (1) develop an advanced fluid bed heat exchanger for an aluminum melting furnace that will push the state-of-the-art from 700°F to 1100°F; (2) conduct laboratory tests on materials; (3) conduct laboratory tests on the heat exchanger; (4) install and test operation in a furnace at Alcoa; and (5) study potential for further increasing inlet temperature capability to 1600°F and above (2 month study) and recommend R&D. This document summarized the results of the item (2) study.

It has been previously shown in the summary section that higher temperature capability gives a smaller size unit with lighter weight and substantially lower cost while the amount of energy recovered increases dramatically. A survey of over 15 aluminum industry companies which have a substantial number of furnaces with high temperature exhaust was made to establish the requirement for heat recovery.

The restriction on space in the areas that high temperature furnaces are located is severe. Over 80% felt that the size and weight of a unit would be very important in the decision on its utilization.

All of the surveyed aluminum companies said that the energy conservation effort is limited by equipment cost because of short capital availability, fouling risks and maintenance factors. Productivity is often limited by maintenance. Industrial plants do not want to introduce additional equipment that requires substantial maintenance. The fluid bed heat exchanger is very appealing from this standpoint, however, further improvement on the size weight and cost are very much of interest and the higher temperature capability makes the needed improvements in these areas.

3.0 DESIGN DESCRIPTION

In order to acquaint or re-acquaint the reader with the basic concept of the fluid bed waste heat recovery system, the next few pages will address a brief description. Figure 1 is a pictorial of the concept.

The concept includes fluid bed heat transfer for the waste heat recovery which provides ultra high heat transfer coefficients and allows a substantial potential for technology advancements utilizing that capability.

The type of heat transfer of interest is gas to liquid or gas to vapor in that the largest amount of waste heat is in the gaseous form and the most useful form of heat derived is in the liquid or vapor form such as steam.

The concept limits the fouling to a single flat plate which can be cleaned mechanically in a positive manner. The tubes for heat transfer are imbedded in the fluid bed and are gently cleaned by the positive scrubbing action of the bed particle. Heat transfer capability is extended by the use of the fluid bed ultra high gas film coefficients and by the fact that the equipment is kept clean so that performance is not degraded with time. The unit has substantial inherent corrosion tolerance due to the low temperatures of most of the equipment.

The concept has a substantial extension of capability from current design in the following areas. The unit is self cleaning and does not require periodic cleaning. Although limited in temperature of the incoming waste gas, the present contract will increase the temperature capability from 700°F to 1100°F with potential to at least 1800°F with additional R&D. The concept to be utilized has a positive control method for elutriation developed by Fluidfire which utilizes a screen accordioned and placed over the bed to deflect elutriated bed particles back into the bed.

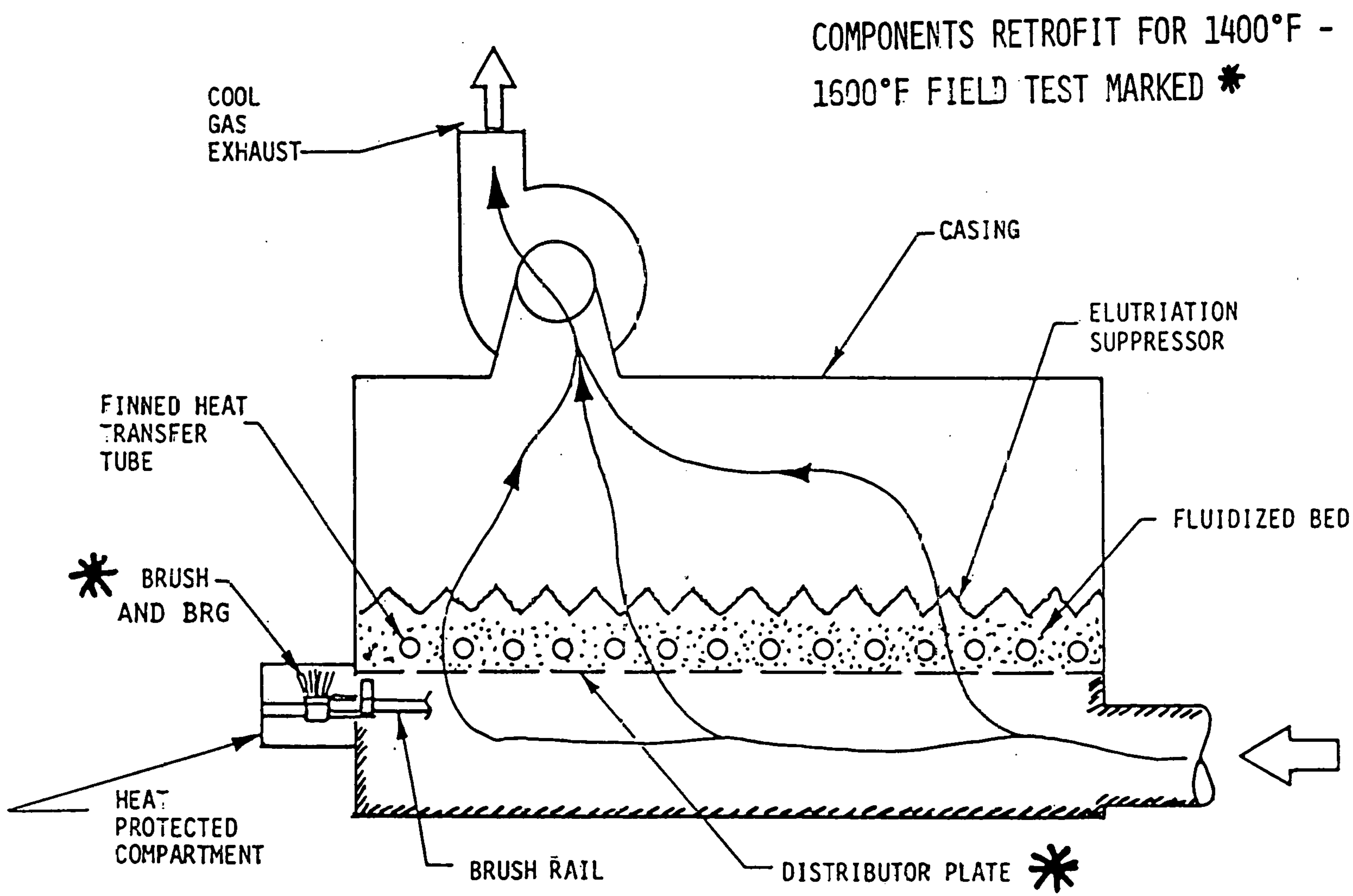
The concept includes self-controlled draft which controls flow pressure and shutoff within the unit so that it does not give a negative impact on the furnace that it is attached to.

A general layout in a conceptual form of the fluid bed waste heat recovery system is shown on Figure 1. The hot gas enters the unit at the bottom on the right and is evenly distributed across the distributor plate due to the inherent pressure drop of several inches of water across the slots in the plate. The inlet area is insulated and the brush and brush track assembly are used to clean the bottom surface of the distributor plate. The brush and the bearing on which the brush rides are maintained in a heat protected compartment except for the small percentage of time in which it must traverse the distributor plate.

The fluidized bed is about 5 inches thick when expanded and covers the finned heat transfer tube. Just above the fluid bed the elutriation suppressor screen prevents most of the particles from carrying over into the exhaust.

The gas exhaust is cooled from the instant it enters the fluidized bed to an equilibrium temperature which is only about 100° above the temperature of the steam or water in the heat transfer tube; this is typically about 500°F. Thus, the bed, tubes, elutriation suppressor, upper casing, and exhaust fan are at a temperature of approximately 500°F or less. The induced draft fan at the top of the unit draws the cool gas exhaust out and either directs it back into the stack or becomes its own stack.

The components that are to be retrofitted for the higher temperature field tests are marked with an asterisk. These are the only components that are effected by the higher temperature.



8

Figure 1. FBWHRS Concept - General Layout

3.0, Design Description (cont.)

The bottom side of the distributor plate and the stainless steel brush mechanism with its track and trolley arrangement and with its pull chain are shown on the photograph below, Figure 2.

This equipment will be further developed to increase its operating temperature capability, especially the parts that are exposed directly to the hot gas. Much of the discussion that follows will be pertaining to the equipment shown in this photograph.

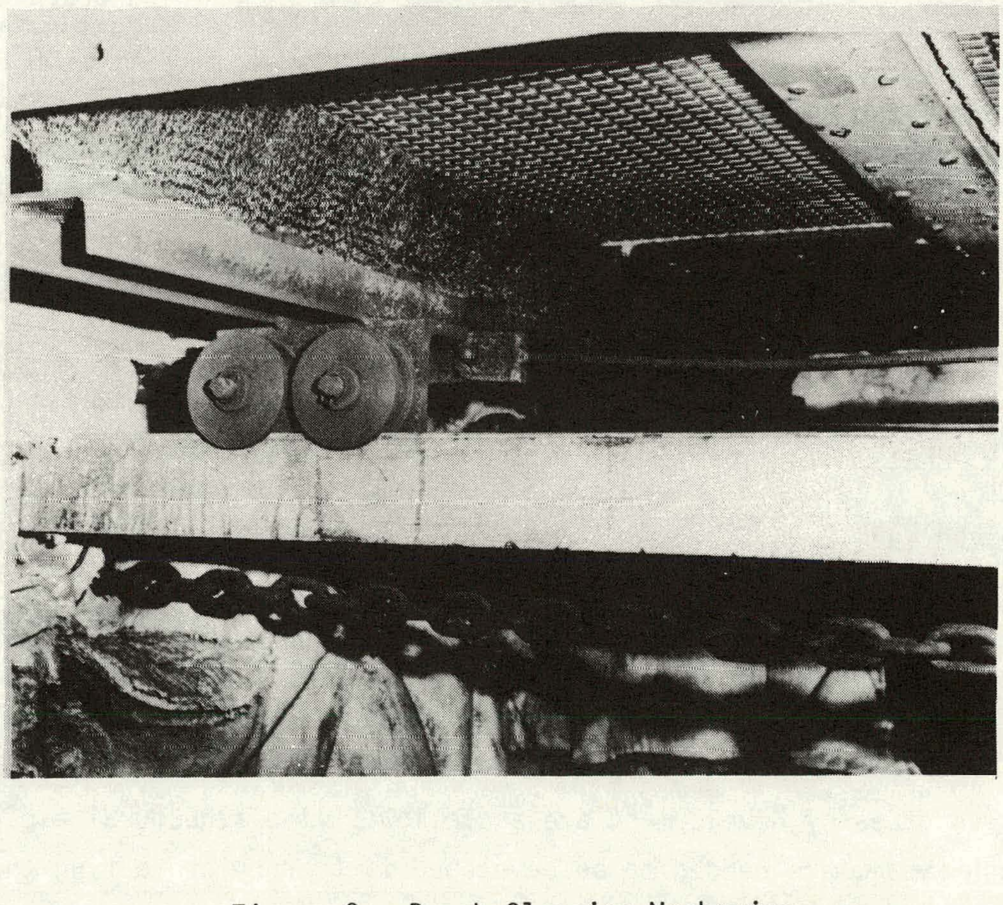


Figure 2. Brush Cleaning Mechanism

4.0 TECHNOLOGY APPROACHES FOR 1100°F CAPABILITY

Table 2 below is a compilation summary of the state of technology and areas of development needed to achieve 1100°F capability.

TABLE 2

PRELIMINARY YES→NO GRID ANALYSIS
(AT 1100°F)

	TECHNOLOGY ESTABLISHED?	REMARKS
1. Inlet Section (Windbox)	Yes	Same as Ducting
2. Brush System		
A. Structural	No→Yes	Bearing Protected Plus Creep Strength/ Corrosion/Fouling are OK at 1100°F
B. Brushing Ability	Yes (Dry)	
3. Distributor Plate		
A. Plate	No→Yes	OK to 1200°F Metal Temp.
B. Support Strength	Yes	Creep Strength Good to 1100°F
C. Corrosion	No→Yes	Dry Particles + FJORDSHELL 700°F
4. Grit Arrestor	Yes	Check HX Surface Driving Bed Temp.
5. Fan and Case	Yes	Same as Arrestor

The technology is established in the areas of the inlet section, brushing ability, distributor plate support strength, grit arrestor, and fan and case.

The areas of development are as follows. The structural aspects of the brush system are needed to be developed further by protecting the bearing that the brush system rides on.

4.0, Technology Approaches for 1100°F Capability (cont.)

The distributor plate has not been operated at 1100° in a fouling environment, however, tests have indicated that a metal temperature of up to 1200°F is satisfactory. Corrosion rates have not been measured at these temperatures. However, the experience of the Fjordshell installation at 700°F under corrosive conditions is one indication that the equipment is tolerant of corrosion.

The crucial factor is that the particles are anticipated to be dry at temperatures of up to 1100°F and thus the corrosion is expected to be small. Corrosion tests at ORNL are a key factor in projecting success.

5.0 HIGH TEMPERATURE PROBLEMS

The various technical problems that are imposed by increasing inlet temperature above 1100°F will be reviewed in this section.

One of the main problems with increasing temperature is that there are particulates in the aluminum furnace exhaust stream that become sticky and molten at temperatures above 1100°F. Brush systems previously used for cleaning the distributor plate are not designed to remove particulates that are sticky. Rather the design is oriented towards brushing dry particulates that are loosely attached to the distributor plate.

The primary source of these particulates are from ash and chemicals in the fuel. Those elements include vanadium, sulphur, chlorine, potassium, and sodium. The particulates listed below are known to become softened and partially or fully molten at temperatures between 1100° and 1600°F. Although other compounds are potential problems, these are the primary ones that are in enough quantity to cause a brushing problem. Eutectics of these elements can also be formed which can modify the temperatures at which they initially become sticky.

POTENTIAL STICKY PARTICULATES

VANADIUM PENTOZIDE	SODIUM SULPHATE
ALUMINUM CHLORIDE	POTASSIUM SULPHATE
ALUMINUM SULPHATE	SODIUM CHLORIDE
POTASSIUM CHLORIDE	POTASSIUM OXIDE

Another key problem with higher temperatures is the thermal stresses on the slots of the distributor plate. This problem has been established in laboratory tests and is due to the fact that the slot bridge sees the inlet gas flow on both sides of the metal bridge.

Since the bridge is essentially uncooled and is very nearly at the full inlet gas temperature and yet the distributor plate is well cooled by the fluid bed, then it stands to reason that very severe differential thermal expansion will induce heavy local stresses at the edges of the slot.

It has been found in laboratory testing that a temperature of 1200^{o}F is critical in this respect as long as the slots are pointed downward. It was also found, as mentioned above, that the slots must be pointed downward in order to be brushed.

Higher inlet temperature reduces the amount of air dilution and therefore the throughflow and the bed plan area. Since the amount of heat transfer increases at the same time, the amount of heat exchange surface per bed plan area increases significantly. This requires closer spacing of the heat transfer surfaces and higher packing density.

Increased temperatures generally increases corrosion rates. The alternatives are to (1) reduce the temperature by cooling or insulation; (2) use a material more resistant to corrosion; or (3) make no change if the corrosion rates are acceptable.

Another key problem with high temperature is the creep strength reduction for the distributor plate supports. The distributor plate is supported necessarily on a long span of approximately 12 feet. The plate supports must be exposed to the full inlet gas temperature with the current design. Creep strength is reduced substantially as temperature increases and, therefore, an increased section must be used. Methods to limit the temperature of the metal have been explored and will be discussed later.

The brush bearings and trolley arrangement which provide the cleaning system for the distributor plate are exposed to the hot gas temperatures. It is possible that they could be shielded for the period of their inactivity which is over 99% of the time; however, they will be periodically exposed to the high temperatures.

The present design uses molybdenum disulfide lubricated bearings and the proposed temperatures would be too high for that design. More advanced bearing designs which can tolerate the temperature, but are not excessively heavy, must be investigated. Bearings used in tunnel kilns would be applicable except for their excessive weight. Consideration of ceramic type bearings must be taken.

There are, of course, risks of unknown factors which are not now predicted. Laboratory testing must be conducted in order to establish these factors and find acceptable solutions.

6.0 FOULING CONSIDERATIONS

6.1 GENERAL

The next section will deal with the fouling aspects of concern as temperature is increased above 1100°F. The amount of data available on particulates in aluminum melting furnaces is quite limited. This is true of Alcoa furnaces as well as those of other companies in the business. One problem is that there is substantial variation from furnace to furnace due to wide variations in scrap loading, scrap content, fluxing, and fuel type.

Alcoa has taken measurements on a large furnace at the Massena, New York plant and the results are currently being analyzed. A report will be available in the near future.

The Alcoa experience to date shows that the exhaust is quite dirty and that generally the particles are fairly dry when proper additives are used. The fuel additives which have been tried in the past render the vanadium pentoxide particulates mostly dry. When a Corepak ® heat exchanger was used in the exhaust as a convective recuperator it was plugged up in a matter of a few days due to the dirty exhaust.

A survey of the sources of particulates from the Alcoa furnace divides the sources between the fuel and the melt. Fuel sources are: ash comprised of minerals which are not combustible, sulfurous oxides, unburned hydrocarbons and char, and mineral additives which have been slurried in the fuel.

Particulate sources from the melt itself are primarily alumina. It is generated by the severe turbulence of the combustion products high velocity flow over the top of the melt. Aerosol size particles of alumina are generated. There are also traces of chlorides (primarily aluminum chlorides) and magnesia from the magnesium in the metal in very small amounts.

6.1. General (cont.)

The other main source of particulates is from the interaction of the products of combustion and the melt. This generates aluminum sulfates, magnesium sulfates, alkali oxides, alkali chlorides, and alkali sulfates in small amounts. The typical particle size is several microns.

6.2 FUEL SOURCES

Since a major part of the particulates come from limits within the fuel, the fuel specification that Alcoa uses was surveyed. Key data on the fuel specification are shown on Table 3.

TABLE 3
ALCOA FUEL SPEC

PITTSTON PETROLEUM INC.
NO. 6 FUEL OIL (2.8% SULFUR)

	Control		Typical
	Min.	Max.	
Visc., SSF @ 122°F	131	200	196
Sulfur, ASTM	-	2.8%	2.70%
Ash	-	0.10%	-
Pour Point, ASTM Deg. F	-	600	450

Alcoa uses No. 6 fuel oil for most of the year with the capability of shifting to natural gas for brief periods. The oil is high sulfur and high vanadium content fuel that will meet the cost requirements of their process.

6.2. Fuel Sources (cont.)

The allowable sulfur is 2.8% and typically it is near the maximum level at 2.7%. The ash content is typical of #6 fuel oil at 0.10%.

It is the sulfur ash and vanadium that are the key problem areas for fouling in the heat exchangers for aluminum melting furnaces on No. 6 oil.

6.3 GAS COMPOSITION

The gas composition in the Alcoa melter exhaust is the result of the combustion of #6 oil with the addition of diluent air to bring the temperature down to 1100°F as a baseline value.

The gas composition for that temperature is shown on Table 4.

TABLE 4

ALCOA MELTER EXHAUST

GAS COMPOSITION (VOL. % AFTER DILUTION AND AT 1100°F)

N_2	77.1	CO_2	15.1
O_2	2.0	H_2O	4.0
SO_2	1.4		

Traces of:

CL	SO_3	
AL CL	HCL	(Sublimes @ 352°F)

The gaseous species that are of special interest are the SO_2 at 1.4% volume and the traces of chlorine, SO_3, aluminum chloride, and hydrogen chloride. These species are of interest with respect to potential corrosion at higher temperatures.

6.3. Gas Composition (cont.)

As the temperature is increased the diluent air flow is decreased. The volume percentages of the SO_2 will therefore increase to the point where at 1800°F it will be nearly double that at 1100°F.

6.4 MAJOR CONSTITUENTS

The major constituents of the particulates in the exhaust stream are identified in Table 5. The key constituents are aluminum oxide, aluminum sulfate, and the various vanadate forms of vanadium pentoxide.

TABLE 5

ALCOA MELTER PARTICULATES

MAJOR CONSTITUENTS

Constituent	(°F) Melting Temp.	Phase Condition at Gas Temp. (°F) 1100	1600	1800	Potential Problem
Aluminum Oxide	3713	Solid	Solid	Solid	No. will brush
Aluminum Sulfate	1418	Solid	Gas	Gas	Probably, Above 1200°
Vanadium Pentoxide (Various Vanadates)	1200 & up(1)	Dry Solid	Sticky Solid	Sticky Solid	Probably, Above 1100°

(1) Melting Point Examples: Sodium Vanadylvanadate 1160°F; Sodium Metavanadate 1165°F; Sodium Pyrovanadate 1185°F; Sodium Orthovanadate 1560°F

The aluminum oxide does not cause a problem with respect to becoming sticky or molten in that its melting temperature is well above the temperatures that will be experienced in the exhaust. It will therefore brush satisfactorily.

6.4. Major Constituents (cont.)

Aluminum sulfate will have a melting temperature and softening temperature within the temperature range of interest and can be a problem at any temperature above 1200°F. Aluminum sulfate goes to the gaseous form at a temperature of approximately 1400 to 1600°F. In the presence of other particulates it could be a problem with respect to stickiness at any temperature above 1200°F.

The vanadates are potentially a serious problem in that they have melting points ranging from 1160° to over 1500°F. At 1100°F, however, it would be a dry solid and would not be a problem in that it would be brushed readily by the brush system. At 1600°F and 1800°F, it would be in the form of a sticky solid.

6.5 MINOR CONSTITUENTS

The particulates in the Alcoa melter exhaust that are relatively minor constituents are listed in Table 6. The melting temperatures and the phase conditions at gas temperatures in the range of interest are given. The nature of the problem potential is also commented on.

TABLE 6

ALCOA MELTER PARTICULATES

MINOR CONSTITUENTS

Constituent	Melting Temp. (°F)	Phase Cond. at Gas Temp. (°F) 1100	1600	1800	Potential Problem
Sodium Sulfate	1623	Solid	Sticky Solid	Liquid	Probably, Above 1400°
Potassium Chloride	1429	Solid	Liquid	Liquid	Probably, Above 1200°F Except Only Trace Amount

6.5. Minor Constituents (cont.)

TABLE 6 (cont.)

Constituent	Melting Temp. (°F)	Phase Cond. at Gas Temp. (°F) 1100	1600	1800	Potential Problem
Potassium Sulfate	1956	Solid	Solid	Solid(2)	Possibly, Above 1700°
Sodium Carbonate	1564	Solid	Liquid	Liquid	Possibly, Above 1400°
Potassium Carbonate	1636	Solid	Solid(2)	Gas(3)	Possibly, Above 1400°
Potassium Oxide	662	Gas (Decomp.)	Gas	Gas	Not Likely
Sodium Chloride	1474	Solid	Liquid	Liquid	Probably, Above 1300°
Sodium Oxide	2327	Solid	Solid	Solid	No

NOTES: (1) Eutectic mixtures of above compounds will likely have reduced melting points.

(2) Possibly sticky

(3) Decomposes rather than melt transition.

The constituents which are probable potential problems are sodium sulfate, potassium chloride, and sodium chloride. These have softening temperatures that are occurring between 1200° and 1600°F. These will be minor constituents because the sodium and potassium is derived from the ash in the fuel and the chloride is limited to chlorine in the fuel and trace amounts in the combustion air.

The possible problem particulates are potassium sulfate, sodium carbonate, and potassium carbonate. These can be problems at temperatures above 1400°F. Again, the potassium and sodium are limited by the small amounts in the fuel ash. The carbonate and sulfate elements are readily available from the products of combustion.

The potassium oxide has a very low decomposition temperature and is not likely to be a problem. The sodium oxide has a very high melting temperature and would not be a problem for that reason.

It should be noted that eutectic mixtures of these various compounds will likely have melting points that are below those of the separate compounds individually.

6.6 FUEL ADDITIVES

Alcoa has used magnesia additives for the fuel in order to control the vanadates and is willing to use those additives in conjunction with the fluid bed heat exchanger. As can be seen from Figure 3, the addition of magnesium as an additive in the fuel changes the liquidus-solidus interface temperatures. Melting temperature is increased as the magnesium to vanadium ratio is increased. Below 1200°F it is dry particles under all conditions of eutectic formation. The magnesium to magnesium plus vanadium atomic ratio of 0.4 would provide protection at up to 1800°F.

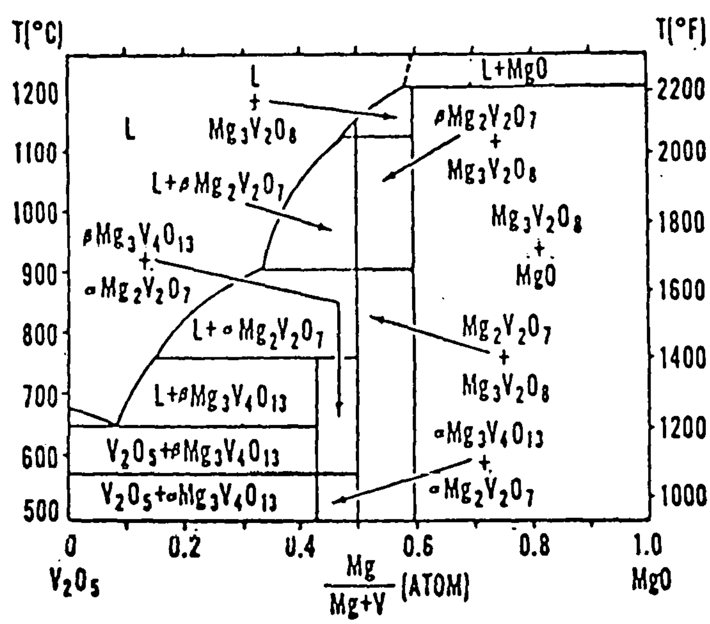


Figure 3. Magnesia Additive Effect on Vanadate Melting Temperature

6.0. Fouling Considerations (cont.)

6.7 ADDITIONAL DATA

Various data that are pertinent to the investigation is summarized on Table 7.

It is clear that aluminum furnaces operating on #6 oil will foul most types of heat exchangers fairly quickly. It is also clear that temperatures above 1200°F are the problem areas.

Laboratory work to establish the temperature "windows" at which the particulates will be dry is important to eliminating fouling problems in exhaust equipment. Key problems will be in the alkali sulfates and vanadates and particular attention must be given to these compounds in that they not only cause fouling but can cause rapid corrosion as well.

TABLE 7

ALUMINUM FURNACE AND/OR NO. 6 OIL PRODUCTS OF COMBUSTION

FOULING DATA SUMMARY

SOURCE	
B&W	- Fuel oil ash softens and melts over temp. range dependent on composition. Seldom has single sharp melting point. Progressive fouling usually only above 1000°F metal temp.
Alcoa	- Close passage heat exchanger can foul in days.
Midland Ross	- Heat wheels not suitable in alum. melter applic. due to fouling.
Kaiser	- Fouling is chief limitation on alum. heat recovery.
Hague Intl.	- One year life with good maintenance - several mos to foul up w/o maint. (convect. recup.)
Battelle	- Aluminum flue gas data base (incl. transient) needed for severe fouling. Coatings can protect for corrosion.
Aerojet	- Temperature window lab determination can help. Alkali sulphates can plug distributor plates.

6.7. Additional Data (cont.)

Table 7 (cont.)

AiResearch	- Lab tests 220 hrs, Na_2SO_4 200 ppm difficult to clean adequately.
Metals Engrg.	- 1100°F to 1200°F is lower limit of most fuel ash deposit/ corrosion problems. Rapid corrosion possible above 1100°F.
C-E	- Corepak has had fouling problems with #6 on melter.
Fluidfire	- Brush works well if particles dry - no sticky experience
ORNL	- #6 oil ash burden and fuel impurities can cause problems at high temp.
Pechiney	- Alum. melter WHB foul up with fins even on N.G. Kept temp. < 800°F.
Other	- Eutectic sodium sulfates can't be soot blown well - can be brushed - magnesia helps ° Alkali sulphates (NA,K) and vanadates are most common problem. ° Low excess air is usually beneficial (negated by dilution). ° Fuel additives can help - tests needed for specific applications.

Additional data obtained is summarized on the next page. This data further substantiates the conclusions.

The eutectic sodium sulfates have been found to be difficult to handle by soot blowing; however they can be brushed especially if magnesia additives are used. Our need to have diluent air goes against the usual advice of having low excess air for minimizing fouling, however there is no way around using some air dilution.

A bibliography is included at the back of this report for further reference.

6.0 Fouling Considerations (cont.)

6.8 OVERVIEW

An approximation of relative values summarizing the fouling conditions with increasing temperature are shown on Figure 4.

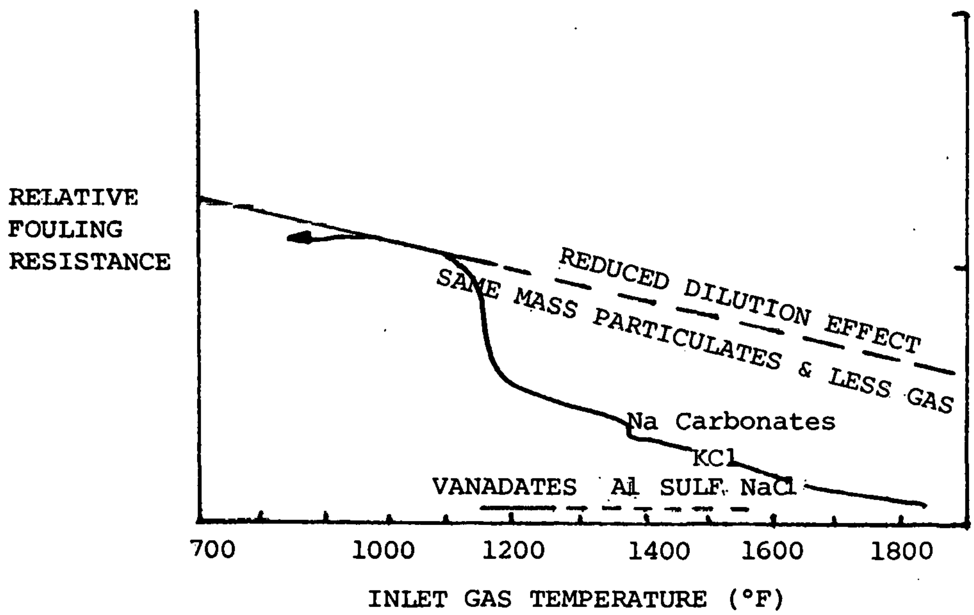


Figure 4. Relative Fouling Resistance vs. Temperature

The line sloping downward labeled "reduced dilution effect" shows that the relative fouling resistance will be reduced as temperature is increased. This is due to the fact that the dilution air introduced has its flowrate reduced and therefore the concentration of fouling particulates is increased. This line is dashed because it does not consider the stickiness of particulates at temperatures above 1200°F.

6.8. Overview (cont.)

On the bottom of the graph the various particles that can cause fouling by softening at the various temperatures are shown as bars representing their temperatures at which they are at molten states. The line of relative fouling resistance departs from the straight line and shows substantial reduction due to the vanadates and other materials which greatly reduce the fouling resistance of the system.

6.9 METHODS OF FOULING CONTROL AND TECHNICAL APPROACH

Methods of controlling fouling have been reviewed. Between 700°F and 1100°F gas inlet temperature, the particulates are expected to be dry and be brushed by the brush design that is planned to be used at the Alcoa tests. Ash products from heavy oil have been brushed successfully below 700°F on Fluidfire units. The behavior is projected to be the same up to 1100°F.

Initial tests at Alcoa will be conducted in the 700 - 900°F range and a gradual increase made to 1100°F with careful monitoring of fouling. This will minimize any risks of undue degradation.

It is concluded from the review of the literature and experience of other in fouling control that any testing at Alcoa above 1100°F should be proceeded by laboratory tests. These tests should establish critical temperatures and the effects of sticky particles on the brushing system. The data will provide cursory type information rather than exact simulation because exact simulation is not possible or practical.

The important factor is that the full range of chemistry and temperatures that are possible in the exhaust stream be tested. It is also important that laboratory tests be oriented towards finding design solutions that are tolerant of the full range of chemistry/temperature condition and not be dependent solely on establishing temperatures at which the design will work.

7.0 THERMAL STRESSES ON DISTRIBUTOR PLATE SLOTS

The fluid bed heat recovery system uses a distributor plate with a baseline configuration of punched slots that are described as "bridge" types. This is because the thin distributor plate, which is approximately 1/16 to 1/8 inch thick, is impressed by matching dyes to generate a configuration that resembles a bridge. This is shown on Figure 5 below.

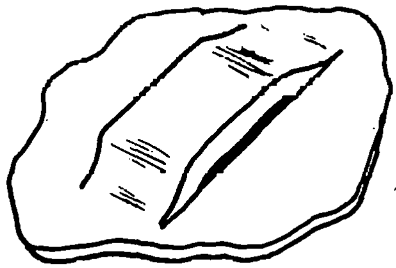


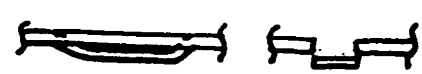
Figure 5. Bridge Slot

There have been laboratory tests conducted on the fluid bed units with the bridge design. These tests have indicated that the bridge metal temperature must be kept below 1200°F approximately.

Additional test results, shown in Table 8, indicated that if the bridge is oriented up so that it is in the bed, then it is adequately cooled by the fluid bed so that the inlet gas temperature can be taken to at least 1800°F.

TABLE 8

DISTRIBUTOR PLATE SLOT TEST RESULTS

Bridge Orientation	Bridge Metal Temp.	Brush Cleaning Ability	Configuration
UP	LOW - COOLED BY BED	NO GOOD - CAN'T CLEAN IN SLOTS.	
DOWN	HIGH - MIN. BED COOLING	CLEANS SLOTS VERY WELL.	

7.0, Thermal Stresses On Distributor Plate Slots (cont.)

There is a critical problem however, in that in this configuration the brush cleaning mechanism will not clean the slots adequately. If the bridge is in a down position so that the slots can be cleaned adequately, there is the dilemma that both faces of the bridge, the upward face and the downward face, are experiencing high velocity and turbulent gas flow at the full inlet gas temperature. This combined with the low thermal flux that can be maintained at the ends of the bridge gives very high metal temperatures. Therefore the problem is that the concept that is adequately cooled cannot be adequately cleaned.

There are several R&D approaches that can provide solutions. The first approach is to use the bridge in the down position so that it can be cleaned and use an insulating sheath as shown in the lower figure on the facing page. The insulating sheath will keep metal temperatures adequately low to prevent inducing cracks. The difficult part is to attach the sheath at a single point or at positions which will not induce thermal stresses in the sheath itself.

Another approach is to use the bridge up arrangement so that it is cooled adequately and use alternative methods of cleaning such as steam blasting. A third alternative is to revise the configuration of the bridge down arrangement but to change to a lip type that has three of the four faces of the slot drawing heat away from the lip.

Figure 6 shows a combination of lip slot and sheath.

Figure 6. Lip-Type Slot with Sheath

8.0 CORROSION

8.1 GASEOUS CONSTITUENTS

The gaseous constituents in the gas stream that represent corrosive problems are listed in Table 9 below. The SO_x elements are the first on the list because of their relative volume quantities. There is only slight trace amounts of chlorine from the atmosphere in the cast house and the fuel ash so that these are almost negligible.

TABLE 9

CORROSIVE CONSTITUENTS IN GAS STREAM

Gaseous

SO_2	1.4%
SO_3	TBD
CL	Trace
AL CL	Trace
HCL	Trace

Particulates

Vanadates (Corrosive when molten and catalyst for $SO_2 \rightarrow SO_3$)

The particulates that are especially corrosive when molten are the vanadates and alkali sulfates. The vanadates have been studied widely and the alkali sulfates as well. The latter are currently beng investigated by ORNL and are responsible for what is called low-hot corrosion.

8.0, Corrosion (cont.)

8.2 CYCLIC CONDITIONS

The conditions in the exhaust of Alcoa melter as relate to corrosion include the modes of operation and cyclic conditions of the temperature as shown on Figure 7.

- THREE MODES OF OPERATION ARE KNOWN

	DUTY CYCLE (HRS)		
	HIGH FIRE	LOW FIRE	OFF
1. SCRAP + MOLTEN	2 1/2	1	1
2. MOLTEN	1	5	1
3. SCRAP	4	2	1

- FBWHRS INLET

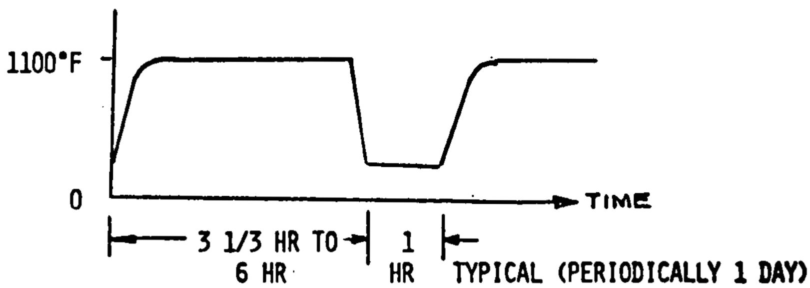


Figure 7. Cyclic Exhaust of Alcoa Melter

There are three modes of operation of the furnace. These are high fire, low fire, and off. Furnace firing rates are 34, 12, and 0 million Btu's per hour, respectively.

There are three general conditions of operation with respect to the material loaded. These are scrap combined with molten metal, molten metal alone, and scrap alone. These are used in various combinations and require different duty cycle times which are shown in the facing table. It is seen that the percentage of off-time is quite low.

The other factor is the cyclic conditions of temperatures in the exhaust. During the off-time the temperature is reduced drastically below the peak operating temperature of 1100°F.

Various melters have different shapes of curves depending on the loading conditions and firing range. The Alcoa melters duty cycle is closer to a square wave than most other melters.

With respect to projecting severity of corrosion the cyclic conditions are very much of interest and will be discussed further.

8.3 MATERIALS OF CONSTRUCTION

The materials of construction which have been selected for the baseline design are listed on Table 10 for the component parts which are expected to be affected by increasing inlet temperature.

TABLE 10

BASELINE MATERIALS

Distributor Plate	RA 330
Brush System	Stainless Type 304
Distributor Plate Support	Low Carbon Steel
Housing Insulation	Castable Fiberglass

8.3, Materials of Construction (cont.)

The components that are affected are the distributor plate, brush system, distributor plate support, and housing insulation.

The distributor plate will operate at a higher temperature due to the increased temperature on the lower face, however this will be mitigated by the high rate of cooling from the fluid bed at about 500°F on the top face. The material which has been planned for use on the baseline design is RA330 generally known as Incalloy 800.

The brush system is exposed to the full gas temperature for very short duration of time measured in seconds. The baseline material for the brush is stainless steel type 304.

The distributor plate support is partially cooled by the fluid bed in the same way that the distributor plate is. It does have to provide structural support at fairly high temperatures and low carbon steel is planned for temperatures up to 1100°F.

The housing insulation on the inside of the inlet windbox is a castable fiberglass. It is of the type used in high temperature gas plennum chambers and ducts.

8.4 METAL TEMPERATURES

Preliminary estimates of the maximum metal temperatures of the components that will be affected by increased gas temperatures are shown on Table 11.

8.4, Metal Temperatures (cont.)

TABLE 11

APPROXIMATE MAXIMUM METAL TEMPERATURES VERSUS GAS INLET TEMPERATURE (°F)

Gas Temperature at Inlet	1100	1400	1600	1800
Distributer Plate				
° Current Design (80% Surface)	800	1000	1100	1200
° Current Design (Local)	1000	1300	1500	1700
° Advanced Potential (100%)*	800	1000	1100	1200
Brush				
° Short Duration Peaks	1100	1400	1600	1800
° Balance of Time	700	800	900	1000
Brush Bearings				
° Peaks	900	1000	1200	1300
° Balance	600	700	800	900
Distributor Plate Support				
Current Design	900	1200	1400	1600
Advanced Potential*	700	800	900	1000

*With Component Design R&D

The listings are given as a function of gas inlet temperature over a range of 1100°F to 1800°F. The first component is the distributor plate and is broken out into three separate categories. The first category is the bulk of the surface of the current design which excludes the slot areas through which gas penetrates. The values given are considered to be conservative and are below 1200°F at even the highest gas inlet temperature.

Local temperatures in the slot and bridge areas of the current design will be very nearly equal to the full gas inlet temperature and are seen to exceed the limit of the 1200° metal temperature before the gas temperature reaches 1400°F. The listing for advanced potential over 100% of the distributor plate is based on concepts such as the inverted bridge or the sheath bridge or cooled slot arrangements. With these it is projected that the metal temperature of 1200 can be maintained even at gas temperatures of 1800°F or above.

The brush is operating under two thermal regimes. The first is the short duration peaks that represent less than 1% of the duty cycle at which the brush is taken to full gas temperature immediately. The second condition or regime is the balance of the time where it is retracted out of the gas flow and is semi-insulated from the hot gas flow. Those temperatures are much lower.

The brush bearings have a condition similar to the brush itself, however, the temperatures are mitigated by the thermal capacity of the wheels and bearing arrangement. Therefore those temperatures are substantially lower.

The distributor plate support is shown with the estimated temperatures for the current design and those with advanced potential which would incorporate concepts of insulation and/or cooling.

8.5 MATERIAL CANDIDATES

Table 12 shows for the various components that are affected by increased temperature, the materials and coating candidates that have been selected in a preliminary way for application consideration. They have

8.5, Material Candidates (cont.)

been divided into metals and non-metals plus combinations of metallic and non-metallic materials.

TABLE 12

MATERIALS AND COATINGS CANDIDATES PRELIMINARY

DISTRIBUTOR PLATE	METALS	NON-METALS	COMBINATIONS
Current Material Rolled Alloy 330 (19% Cr, 35% Ni)	Haynes 188 RA 333 C-276 INCO 601 A-286 Hast C 310 S.S.	Alumina Mullite (AL_2O+SiO_2) Silicon Carbide Aluminum Silicate Magnesium Aluminum Silicate Haynes	Metal + Ceramic *ODS Coatings (Ni-CR-AL) Plasma Coatings
BRUSHES			
Current Material: Stainless Type 304	RA 330 RA 333 Ni-Chrome A-286 Hast C 446 S.S. 310 S.S.	Carbon	Coated Metals
STRUCTURE			
Current Material Low Carbon Steel	Hard Chrome Plated L.D. Steel Diffusion Coating (AL-Fe) onto Carbon Steel Chromizing-Carbon Steel RA 330 310 S.S.	TBD	Coated Metals

*Oxide-Dispersion-Strengthened

For the distributor plate there are a number of metals and non-metals and combinations that can be considered. It is the metals and combinations that are of most interest in that non-metallic materials have substantial other problems of fabricability that would be too imposing. Materials combinations look particularly attractive.

8.6 SLAG CORROSION

The corrosion rates of slag particulates such as the vanadates are of great concern at temperatures above 1100°F. An example of this is data shown on Table 13 where corrosion loss on samples of various stainless steel are shown as a function of metal temperature for temperatures at 1080°F and 1530°F.

TABLE 13

VANADATE SLAG CORROSION VS TEMPERATURE

Metal Temp (°F)	Corrosion Loss (MG/CM^2)		
	347 SS	321 SS	304 SS
1080	40	10	11
1530	750	850	350

NOTE: Fuel additives can reduce these corrosion rates.

One can see the nearly two orders of magnitude increase in corrosion rates with the relatively small increase in temperature. Of course, if the vanadate slags are kept dry by additives or other means, these corrosion rates are kept in check even at temperatures above 1500°F.

The current brush material of 304 stainless steel has many other alternatives with better corrosion resistance and materials properties at higher temperatures. It is possible that non-metals could be used such as carbon fibers if the design is altered to make use of their characteristics such as to have a rotating brush that will gravity load the brush tips. This will get around the problem of the greatly reduced modulus of elasticity and give a controllable tip loading. Combinations such as coated metals can also be considered.

The structural elements are currently of low carbon steel and have many other alternative metals that can be used. There are no non-metals that have been identified as yet which are good candidates, however coated materials could very well be used.

8.7 SUMMARY OF CORROSION PROBLEM AREAS

A summary of the problem areas that could potentially cause concern above 1100°F with respect to corrosion and the solution approaches are listed on Table 14.

TABLE 14

CORROSION FACTORS ABOVE 1100°F

Potential Problems	Solution Approaches
Alkali Sulphate Attack (Low Hot Corrosion)	Use fuel additives and establish temperature windows (1200-1300°F avoid especially)
Vanadium Pentoxide Attack (above 1200°F)	Fuel additive, improved distribution plate cleaning
Sulphur Oxides Corrosion	Reduce nickel content, keep metal temperatures down

8.7, Summary of Corrosion Problem Areas (cont.)

TABLE 14 (cont.)

Potential Problems	Solution Approaches
Stress Corrosion Cracking	Avoid dwelling at $\sim$1200°F
Structural Life (Time-Temp Effects)	Keep chrome content or metal temp. down (<1200°F)
Thermal Fatigue	Limit peak metal temperatures

NOTE: In all cases material selection and advanced design concepts can help.

The first potential problem is the alkali sulfate attack which is commonly termed low hot corrosion. Although this problem can be severe in coal combustion the relatively low ash and therefore low amount of alkalis in the fuel can keep this at a solvable level. This is because there is no fluxing agent including alkalis that are used. That was not the case with the Reynolds Aluminum tests that were run on the recuperator at the Alabama plant. One approach would include the use of fuel additives to increase the softening temperature and also to etablish temperature windows to be avoided. The literature indicates that low hot corrosion is especially of concern at the tempratures between 1200°F and 1300°F.

Vanadium pentoxide attack problems have been discussed in previous pages and the approaches are to use fuel additives and to provide improved distributor plate cleaning. It is felt that the distributor plate cleaning method should not be fully dependent on the particles being dry but should be able to tolerate at least a small percentage of the particles in the semi-molten state.

Sulfur oxides corrosion should be controlled by materials selection keeping the nickle content low and by design concepts which keep metal temperatures down.

Stress corrosion cracking potential problems will be attached by avoiding dwelling at the 1200°F sensitization temperature regime, if necessary. The structural life aspects of corrosion which are based on time and temperature combination effects will be attacked by keeping chrome content and/or metal temperatures down as much as possible.

The thermal fatigue potential problems will be limited by keeping peak metal temperatures low.

In each of the potential problem areas the materials selection and advanced design concepts previously discussed can be of help.

8.8 STRUCTURAL STRENGTH AT HIGH TEMPERATURE

As the metal temperatures of the structure that is supporting the fluid bed distributor plate are increased above 1100°F there is a gradual but very significant reduction in creep strength. Since the metal temperature is generally below the gas temperature for most of the components a plot of creep strength versus gas temperature is not quite so bad; however, it is clear that at temperatures approaching 1800°F the creep strength will be approaching 1/10th the value at room temperatures. The curve on Figure 8 shows this.

It is clearly seen that above 1200°F the technology hurdles are tougher from the standpoint of providing adequate structural strength. This will be further discussed in the next several pages.

8.8, Structural Strength at High Temperature (cont.)

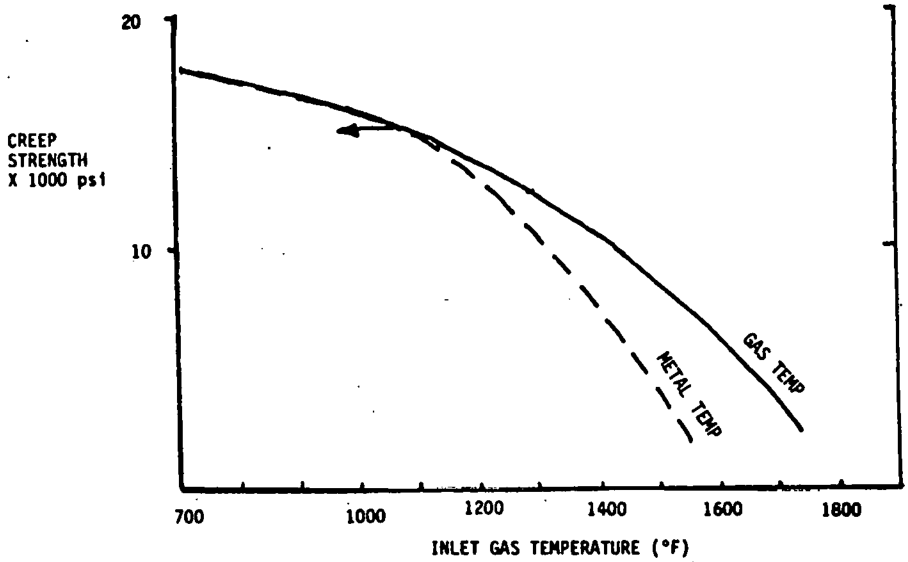


Figure 8. Creep Strength vs. Temperature

The structural element of most concern with higher temperature is the bed support design. Having to span about 12 ft and with vertical supports precluded because of other design factors, advanced concepts will have to be used. In the sketch of Figure 9 the structural support for the bed is shown in cross section with the distributor plates laying on it. The bed and heat exchange tubes are also shown.

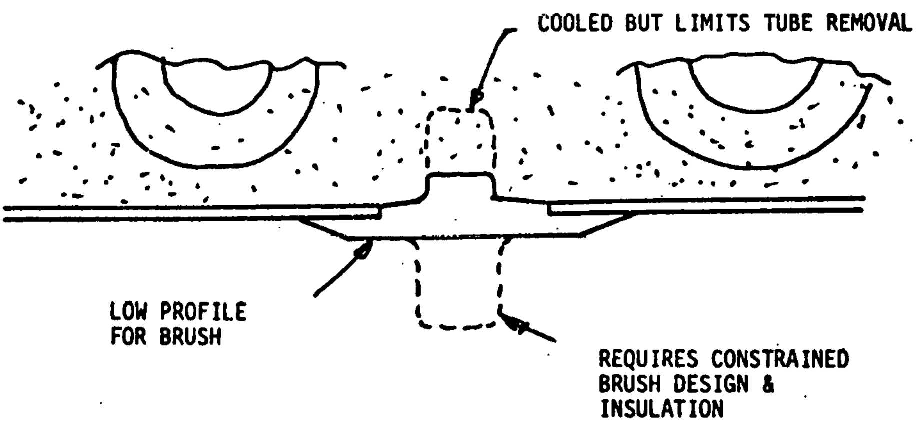


Figure 9. Bed Support Design Constraints

The design constraints on the bed support are shown in dashed lines. There are several constraints. Firstly, the bottom section must have a low profile to allow passage of the brush arrangement. Secondly, extensions into the bed to provide cooling of the support limits tube removal. Some compromise combinations of these elements including consideration of insulation and cooling by water or steam must also be considered.

9.0 TECHNICAL RISKS

The technical risks of increasing temperature will be discussed in the next several pages in order to identify which areas are of major concern. The methodology used here is the yes-no grid which identifies whether technologies are currently established or not.

The various subsystems of the waste heat recovery system are listed on Table 15 with the other dimension of the matrix being three selected temperatures, 1100°, 1400°, and 1800°F.

TABLE 15

PRELIMINARY YES-NO GRID

COMPONENT/SYSTEM	TECHNOLOGY ESTABLISHED?		
	1100°F	1400°F	1800°F
1. Inlet Section (Windbox)	Yes	Yes	Yes
2. Brush System			
A. Structural	No→Yes (Bearing)	No (Creep Strength)	No (Creep Strength)
B. Brushing Ability	Yes (Dry)	No (Sticky?)	No (Sticky?)
3. Distributor Plate			
A. Plate	No→Yes (OK to 1200)	No	No
B. Support Strength	Yes	No	No
C. Corrosion	No→Yes (Dry Particles + FJORDSHELL 700°F)	No	No
4. Grit Arrestor	Yes	Yes	Yes
5. Fan and Case	Yes	Yes	Yes
6. Heat Exchange Surfaces (Higher Heat Transfer Surface Packing Density Must Be Surveyed)	Yes	Yes	Yes

It is seen that the inlet section technology is established for the higher temperatures drawing from duct insulation and design data base. The brush system is divided into structural and brushing ability areas. In the structural area at 1100° the technology is not established but will be by bearing modifications under the current program. At 1400° and 1800° the technology is not established and must be addressed in a separate development. In the area of brushing ability at 1100°, the particles are dry and therefore the established technology can be used. At temperatures above 1100°F to 1200°, the stickiness of the particles will be a potential problem and technology is not established for that.

On the distributor plate the plate itself is satisfactory to a metal temperature of 1200°F and therefore satisfactory operation at 1100°F under the current program is anticipated. At temperature above that the dilema of cleaning versus cooling of the slots must be addressed. The distributor plate support strength discussed in the previous pages, at 1100°F is not a problem. However, because of the more rapid fall off in creep strength at higher temperatures the 1400 - 1800° must be established by more advanced concepts. Distributor plate corrosion parrots the brushing ability from the standpoint that dry particles are much less corrosive and can be tolerated therefore temperatures of 1100° would be satisfactory, however, at higher temperatures with sticky particulates the corrosion would be a factor. In addition there are also the gaseous corrosion elements that have to be considered. All in all the specific corrosion rates at the increased temperatures are not very well predictable without coupon testing.

Additional technical risk areas which have been investigated are the grit arrestor, fan, case, and heat exchange surfaces.

In each of these areas, the operating temperature of the components does not change significantly with increasing inlet temperature. This is because the fluid bed maintains the necessary heat flux with very low temperature differentials. Thus, even though the inlet temperature increases from 1100° to say 1800°F, the bed temperature will increase only approximately 50°F.

For these reasons, the technology is established for each of these components listed for the full temperature range.

10.0 HIGH TEMPERATURE R&D PAYOFF

10.1 GENERAL

Increased temperature capability gives a payoff in a number of very important areas.

Performance is improved by increased effectiveness due to the higher differential temperature that is obtained between inlet and outlet. Thus the heat recovery is greatly improved. A secondary factor, but an important one is that the lower mass flow rate caused by reduced diluent air reduces the fan power required.

Life cycle cost is significantly decreased. Capital costs are reduced because the lower flow rates give smaller bed areas and correspondingly smaller total volume and component sizes. Operating costs are reduced because of the smaller fan power and its impact on electrical costs. Installation is easier and less costly with a smaller unit.

Increased industrial incentive (ROI) is very important to achieving heat recovery implementation and is the ultimate payoff in terms of energy saved. This incentive is increased by higher performance and better return on investment from the reduced cost.

Conducting R&D to achieve higher temperature is very cost effective as a part of this project for several reasons. First of all, existing test facilities can be used for both laboratory and field testing. In addition, the program can move ahead quickly with minimal delay and cost.

10.2 HEAT RECOVERY VS. TEMPERATURE

The heat recovery increase with higher temperature capability is one of the most important payoff factors.

10.2, Heat Recovery vs. Temperature, (cont.)

Heat exchanger efficiency can be approximated as the temperature differences between inlet and outlet divided by inlet and ambient.

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_{ambient}} \qquad \text{where } T_{out} \approx 500^{o}F \text{ and } T_{ambient} \approx 70^{o}F$$

Outlet temperature is generally fixed at about 500^{o} for several reasons and ambient temperature is normally somewhere near 70^{o}F. Data in Table 16 was calculated directly giving efficiency comparisons as a function of temperature.

TABLE 16

HEAT EXCHANGER EFFICIENCY VS. TEMP

T_{IN}	700^{o}F	1100^{o}F	1400^{o}F	1600^{o}F	1800^{o}F
η Recovery	.30	.58	.68	.72	.75
η Rel. to 1100	.52	1.00	1.13	1.23	1.32
*Energy Savings Efficiency	.40	.77	.91	.96	1.00

*Energy Savings Efficiency = BTU saved in fuel for every BTU in exhaust

$$= \frac{\eta \text{ RECOVERY}}{\text{AVE. FIRED BOILER } \eta = 0.75}$$

It can be seen that the efficiency of energy recovery for the state of the art of 700°F is quite low at 30%. It is improved to a very respectable value at 58% at 1100°; however, its potential is not nearly tapped until the temperature is increased to 1600° or higher. This is also shown as efficiency related to 1100° where it is seen that at 1600°F a 23% improvement in efficiency is obtained.

In order to establish an efficiency number which is an overall practical value, the energy savings efficiency is defined as BTU saved in fuel for every BTU available in the exhaust. This is important because the obvious limitation is the amount of BTU's in the exhaust and the bottom line value is the BTU's saved in fuel. The energy savings efficiency can be simply stated as the energy recovery efficiency divided by the average fired boiler efficiency which is usually approximately 75%. From the tabulation of energy savings it can be seen that efficiency is a function of temperature, and at temperatures of 1600 to 1800°F, the efficiency approaches 100%. This means that the BTU's saved in fuel are very nearly the amount of BTU's that are in the exhaust. Achieving these conditions are a very worthwhile goal.

10.3 UNIT SIZE VS. TEMPERATURE

It can be seen from the assumptions, formulae and tabulation on Table 17, that size is reduced substantially as temperature is increased.

TABLE 17

UNIT SIZE VS TEMPERATURE - ASSUMPTIONS & RELATIONS

ASSUMPTIONS

SIZE IS DIRECTLY PROPORTIONAL TO BED PLAN AREA S_B

- BED AREA IS ESTABLISHED BY MAX. SUPERFICIAL VELOCITY V_S, BED TEMP T_B AND ACTUAL GAS VOLUME FLOW $\dot{V}_A$.

RELATIONS

- FOR CONSTANT V_S AND T_B, S_B IS PROPORTIONAL TO $\dot{V}_A$.

- $$\dot{V}_A \Big\}_{TOTAL} = \underbrace{\dot{V}_A \Big\}_{GAS}}_{CONSTANT} + \dot{V}_A \Big\}_{AIR}$$

  ($\dot{V}_A \}_{AIR}$) REDUCES WITH TEMP SINCE LESS DILUENT USED.

- EXAMPLES AT 1800°F AND 1100°F

EXAMPLES	$\frac{\dot{V}\ TOTAL}{\dot{V}_G}$
1800°F: $\frac{\dot{V}_A}{\dot{V}_G} \propto \frac{2100-1800}{1800-70} \approx \frac{300}{1730}$ OR 17%	1.17
1100°F: $\frac{\dot{V}_A}{\dot{V}_A} \propto \frac{2100-1100}{1100-70} \approx \frac{1000}{1030}$ OR 97%	1.97

- RELATIVE VOLUME FLOW AT 1800°F COMPARED TO 1100°F

$$\frac{\dot{V}_A \}\ TOTAL\ 1800}{\dot{V}_A \}\ TOTAL\ 1100} = \frac{1.17}{1.97} = 0.59$$

For the fluid bed heat exchanger, the vertical dimensions are generally fixed by design constraints and the horizontal dimensions, which establish bed area, are variable with the installation and flow requirements.

Size is directly proportional then to the bed plan area taken as S_b. The bed area is established by the maximum superficial velocity that can be allowed and the bed temperature and the actual gas volume flow. Since the superficial velocity and bed temperature are relatively fixed, the bed area is proportional to the gas volume actual flow.

The volume flow is made up of the flow of the gas and the flow of the diluent air combined. Since the air flow is reduced with increased temperature, the total volume flow through the unit is reduced. Example values are shown at 1800^{o} and 1100^{o} in the table.

At 1800^{o} the total flow divided by the gas flow is 1.17, and at 1100^{o} the value is 1.97; therefore, the relative volume flow at 1800^{o} compared to 1100^{o} is 0.59. This means that a 41% reduction in size can be obtained by increasing temperature from 1100^{o} to 1800^{o}.

10.4 RELATIVE COST IMPACT

There are two key factors in the cost impact of higher temperatures. Each will be treated in a relative manner.

The unit acquisition cost is very crucial in the ultimate users decision on whether or not to implement waste heat recovery. With respect to size for a given output there are several considerations.

First, there are cost elements that are proportional to size because of being directly related to material and fabrication labor. These are elements such as sheet metal, other raw materials, fabrication labor, welding, etc. Additionally, there are elements that are not directly proportional to size, and these consist of factors such as engineering labor, steam conditioning equipment, and heat exchange tubes.

Generally, the elements that are not proportional to size are relatively few compared to those that are. An approximation can be taken that sets cost reduction at a rate of about 2/3 of the size reductions. For example, a 10% size reduction will generally give about a 6% cost reduction.

The installation costs are likewise important and vary with size for the same output in a manner similar to those with the acquisition cost. There are elements that are proportional to size, including materials, fabrication labor, support columns, crane rental, etc. There are additional elements that are not proportional to size, including engineering labor, water conditioning equipment, etc. The approximation of cost reductions can be taken at a rate of about 2/3 the size reduction for installation costs as well.

10.5 OVERALL INLET TEMPERATURE INFLUENCES

Table 18 on the following page gives the various influences of the inlet temperature in terms of size, weight, heat recovery and cost. Those elements are then in turn used to derive a figure of merit and relative return on investment data.

10.5, Overall Inlet Temperature (cont.)

TABLE 18

OVERALL INLET TEMPERATURE INFLUENCES

	HX INLET TEMPERATURE			
	1100°F	1400°F	1600°F	1800°F
1. RELATIVE SIZE (RS) & THROUGHFLOW	1.00	0.82	0.71	0.59
2. RELATIVE WEIGHT	1.00	0.83	0.72	0.60
3. RELATIVE HEAT RECOVERY (RHR)	1.00	1.17	1.24	1.29
4. RELATIVE COST (RC)				
• UNIT COST	1.00	0.88	0.81	0.73
• INSTALLATION COST	1.00	0.88	0.81	0.73
5. RELATIVE FIGURE-OF-MERIT $RM = \frac{RHR}{\frac{RC + RS}{2}}$	1.00	1.38	1.63	1.96
6. APPROX. RELATIVE ROI $ROI_{REL} = \frac{RHR}{RC}$	1.00	1.33	1.53	1.77

ASSUMES FURNACE GAS EXHAUST 2100°F UNDILUTED AND STACK MINIMUM 500°F.

The relative size is proportional to the throughflow of gas and is seen to reduce drastically with increasing temperature.

The relative weight reduces nearly as fast as the relative, but not quite due to factors that are not directly linear.

The relative heat recovery increases with increasing temperature such that at 1600°F about 1/4 improvement is made, and at 1800°F a 29% improvement is achieved.

Relative costs of the unit acquisition and installation are reduced significantly because of the reductions in size. At 1800°F the costs are over 1/4 less than at 1100°F.

A relative figure of merit can be derived from the above data. Of course various arbitrary arrangements could be chosen; however, a useful one is to divide the relative heat recovery by an average value of cost and size. This allows equal weighting of cost and size factors. It is seen that the relative figure of merit nearly doubles for the high temperature application and this is significant with respect to the potential payoff in terms of energy recovered in the future.

Approximate relative return on investment increases with inlet temperature to the point where a 50% increase is achieved at less than 1600°F, and 77% increase achieved at 1800°F.

These calculations assume that the furnace gas exhaust is at 2100°F as is typical of aluminum melting furnaces. Also, it is assumed that the stack minimum temperature would be about 500°F, which is likewise typical.

10.6 PERFORMANCE POTENTIAL ABOVE 1100°F

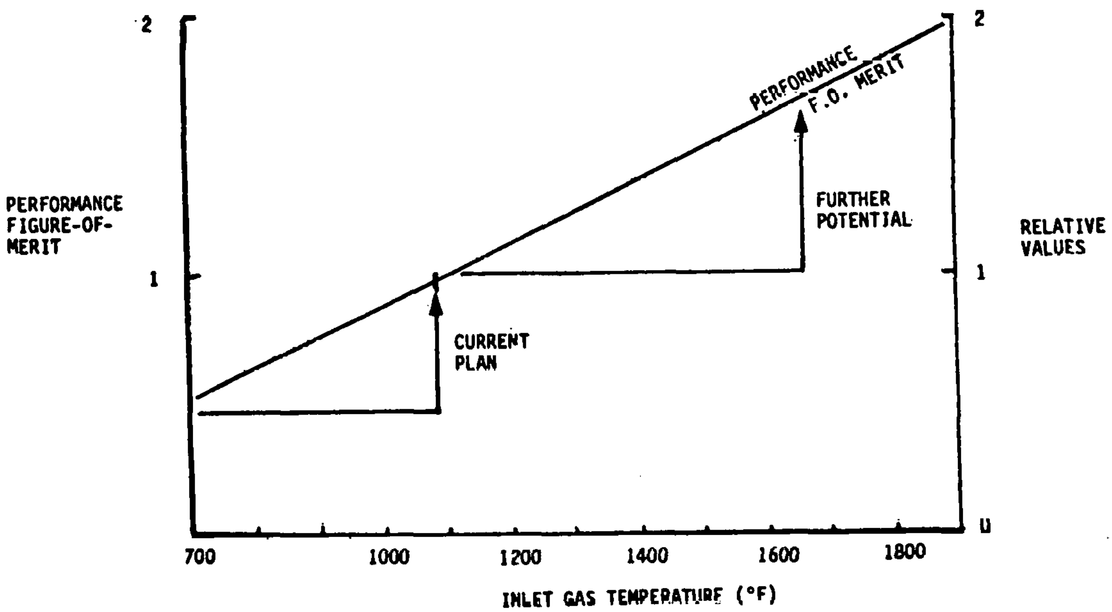
From the graph of Figure 10 we can see that the figure of merit increases dramatically with inlet gas temperature.

If one looks at the increase from 700 to 1100°, a drastic improvement is seen. Likewise, if one compares the 1100° to 1800°F improvement, a drastic change is seen.

The conclusion is that the performance potential of getting to 1100° is a worthwhile ambition; however, it is only scratching the surface of the overall capability of the concept.

Figure 10.

PERFORMANCE POTENTIAL VS. TEMPERATURE



11.0 R&D APPROACHES FOR HIGHER TEMPERATURES

A summary of the performance benefits and the offsetting technology hurdles are shown visually in the combined graphs of Figure 11.

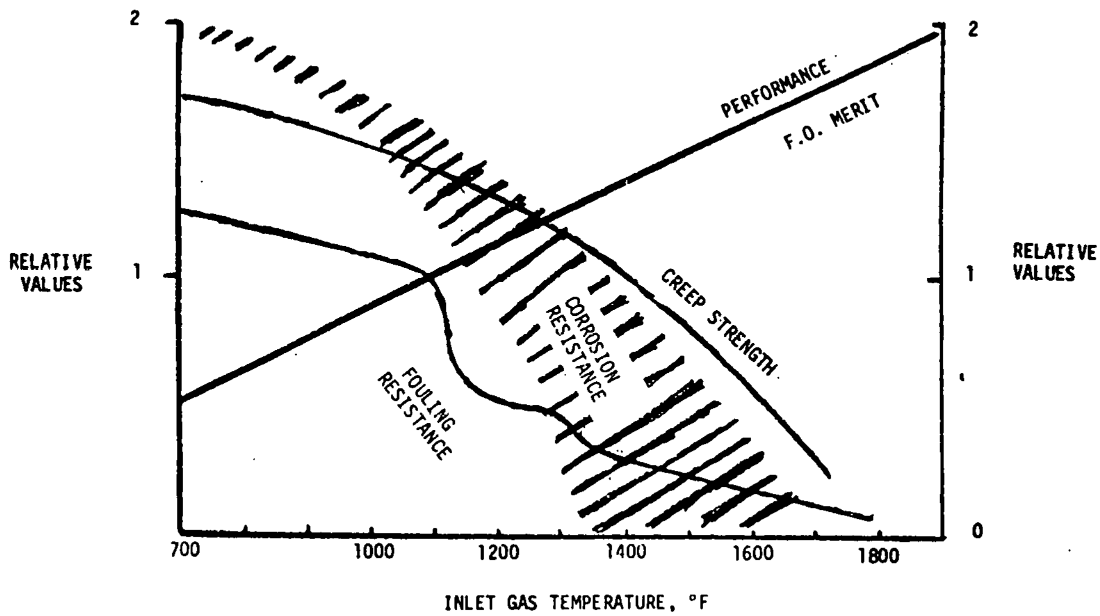


Figure 11. Key Parameters vs. Temperature

While performances doubled over the temperature range of 1100 to 1800°F the technology problems are severe.

Creep strength reduces drastically as previously discussed. Fouling resistance has a step change at about 1100°F due to the sticky particulate.

The corrosion resistance falls more gradually than fouling resistance but does have precipitous potential because of its relationship to the fouling of vanadates and sulfates.

11.0. R&D Approaches for Higher Temperatures (cont.)

On the following pages a summary of the R&D work needed and the approach to be taken will be discussed.

The single major risk to increase temperature is the particulates exhausting from the aluminum melter being too sticky to brush. The R&D approaches to resolve this would include investigation of fuel additives to increase the melting temperature of both the vanadium oxides and the sulfates. Additionally, steam or air jets cleaning would be investigated.

Also methodologies used in other similar anti-fouling work will be used. These have been used successfully at Aerojet for similar applications. They include establishing temperature windows in which the particles are less sticky. Often these approaches are not final solutions but are helpful in facilitating testing.

Another approach is to investigate ways to brush between firing cycles at which time the particulates have dropped in temperature to the point where they are no longer sticky and can potentially be brushed clean. The approach could be augmented by air cooling immediately prior to brushing or during brushing.

The other approach would be to use more advanced brushing concepts including rotating brushes or medium velocity blasting by particulates.

The problem of limiting slot thermal stresses in the distributor plate would be approached by testing revised configurations including the lip and shielded arrangements in laboratory R&D tests. Also, cooling methods using the fluid bed itself or water or steam should be investigated.

11.0 R&D Approaches for Higher Temperatures (cont.)

The increased heat transfer surface density within the bed should be approached by advanced configuration of heat transfer surfaces and closer spacing of the tubes. Staggered tubes could also be used if necessary.

The increased corrosion rate at the higher temperatures should be approached by alternative materials including ceramics and coatings of ceramics and other materials. Additionally, the limitating of metal temperatures is also important.

The maintaining of adequate support strength for the distributor plate at the higher temperatures requires approaches including alternate configuration for reduced temperature, alternate materials for higher creep strength at temperature and insulation for cooling.

High temperature effects on the brush bearings and trolley should be approached by advanced configuration with higher temperature resistance and configurations using thermal capacitants to minimize peak temperatures for the short exposure times.

12.0 RECOMMENDED R&D APPROACH

There are three main elements that should be incorporated in the R&D plan to resolve the problems. The first is to complete a detailed analysis of the problems which would include analyses of alternative designs.

The second element of the approach would be to conduct bench scale tests to establish a technical understanding of the problems and the impact of the selected design approaches. The bench scale testing must be designed to provide a wide range of conditions that will fully bound the Alcoa operating condition. The chemistry and thermal conditions must be especially bounded. The solutions obtained from the bench scale testing must be those that are satisfactory under the full range of conditions rather than being successful only for isolated conditions.

Finally, based on the results of the bench scale tests the best advancements should be retrofitted into the Alcoa test unit and tests conducted with gradually increasing temperature to establish the performance.

13.0 CONCLUSIONS

Several conclusions can be drawn from the previously described study results.

First, the risks of pushing beyond 1100°F in the Alcoa testing are high without an orderly program that includes laboratory R&D and an engineered retrofit of the required component. Of particular concern are the fouling, corrosion, and creep strength reduction problems that are imposed on several elements of the heat exchange system.

It can be concluded also that the benefits of technology advancement for higher inlet temperature capability are remarkably high. For example, a 53% increase in the return on investment at 1600°F and a 77% increase at 1800°F are substantial improvements and worthy of taking on high risk technology advancement.

It can also be concluded that sound technical approaches were established, that can be considered for incorporation into the laboratory development and ultimately into the Alcoa testing.

4.0 BIBLOGRAPHY

1. , Battelle's Multi-Solid Fluidized-Bed Combustion Process - Summary Report on the Status of Development and Commercialization, Battelle Development Corporation, September 1981.

2. , "Reaction with Fuel-Ash Deposits," Metals Engineering Quarterly, May 1968.

3. , "Reaction with Sulphidizing Gases", Metals Engineering Quarterly, May 1968.

4. , Steam/Its Generation and Use, Babcock & Wilcox, 39th Edition, New York, 1978.

5. , U.S. Department of Energy, "Coal Conversion Systems Technical Data Book," HCP/T2286-01, Washington: U.S. Gov. Print, Office, 1978.

6. F. Alexander, "Use of Heat Recovery Equipment in the Aluminum Industry; Light Metal Age, August 1976.

7. D. Anson, et al., "Action of Additives on Fuel Ash Deposits", presented at the Engineering Foundation International Conference on 'Fouling of Heat Exchange Interface; 31 Oct - 5 Nov 1982.

8. H. E. Barbach, et al. "Compatibility Between Furnaces and Fuels Conducive to High Boiler Availability," Power, December 1977.

9. Brock, J.R., "On the Theory of Thermal Force Acting on Aerosol Particles," Journal of Colloid Science, Vol. 17, 1962.

10. Browne, L.W.B., "Deposition of Particle on Rough Surfaces During Turbulent Gas-Flow in a Pipe," Atmospheric Environmental, Vol. 8, 1974.

11. R. W. Bryers, "The Physical and Chemical Characteristics of Pyrites and Their Influence on Fireside Problems in Steam Generators", Journal of Engineering for Power, October 1976.

12. G.D. Colby, "High Temperature Corrosion in Incinerator Heat Recovery Units", Materials Performance, April 1974.

13. Cheremisinoff, P.M. and Young, R.A., Air Pollution Control and Design Handbook - Part I , 1977, Marcel Dekker Inc., New York and Basel.

14. Corn, M., "Adhesion of Particles," Chap. XI in Aerosol Sciences, edited by Davies, Academic Press, 1966.

15. D. Csathy, "Industrial Heat Recovery - 1782", Deltak Corporation, Minneapolis, MN, April 1982.

16. D. Csathy, "Latest Practice in Industrial Heat Recovery" Deltak Corporation, presented at the Energy - source Technology Conference and Exhibition, February 1980.

17. E. DeAnda, Heat Exchanger Fouling and Corrosion Evaluation, Airesearch Manufacturing Company Final Report No. DOE/ET/11796-T21(DOE Contract No. AC22-77ET 11296), 25 October 1981.

18. Derjaguin, B.V., Storozhilova, A.I. and Rabinovich, Ya.I., "Experimental Verification of the Theory of Thermosphoresis of Aerosol Particle," Journal of Colloid and Interface Science, Vol. 21, 1966.

19. R. C. Diehl, J. J. Taber, Jr., and J. L. Walker, "Fireside Corrosivity Studies on Austenitic Stainless Steels used in Utility Boilers", Paper No. 75-WA/CD-g, December 1975.

20. J. I. Federer and V.J. Tennery, Analysis of a Corroded Stainless Steel Recuperator Used on a Glass Melting Furnace, ORNL/TM-7553, November 1980.

21. M. L. Gage, Results of VR Full-Scale Prototype Testing, Aerojet Energy Conversion Company AFY 1980 Final Report, Nov. 1980.

22. Gardwer, G.C., "Deposition of Particles From a Gas Flowing Parallel to a Surface," International Journal of Multiphases Flow, Vol. 2, 1975.

23. Gillespie, T., "On the Adhesion of Drops and Particles on Impact at Solid Surfaces I and II," Journal of Colloid Science, Vol. 10, 1955.

24. H.J. Goldberg and P.A. Kittie, "Impact of Elevated Temperatures on the Reactivity of Alkaline Additives Used to Control 'Cold End' Boiler Corrosion", Journal of the Institute of Energy, [27], March 1979.

25. , High Temperature Range Recuperator, Phase II, Prototype Demonstration and Material and Analytical Studies, Terra Tek, Inc., Final Report No. DOE/CS/40012-2, (DOE Contract No. DE-AC07-77CS40012, April 1980.

26. W. J. Greenlee and R. E. Berger, "Gas Side Fouling Experience in the Waste Heat Boiler of the Sundstand 600 KWe Organic Rankine Bottoming Cycle", paper presented at the Engineering Foundation International Conference on 'Fouling of Heat Exchange Surface', 31 Oct - 5 Nov 1982.

27. G. L. Hanson, "Recuperator Retrofit on an Aluminum Melter", Light Metal Age, December 1976.

28. K. Hein, "Characteristics of Rheinisch Brown Coals with REspect to Their Combustion and Fouling Behavior in Thermal Power Stations," Journal of Engineering for Power, October 1977.

29. Hocking, L.M., "The Collision Efficiency of Small Drops," Quarterly Journal of Research for Society, Vol, 85, No. 44, 1959.

30. L. Kindlimann and R. Silvestrini, Heat Exchanger Fouling and Corrosion Evaluation, Phase I Topical Reprot No. 78-15161 (2), (DOE Contract No. DE-AC03-77ET11296), Airesearch Manufacturing Company of California, 30 April 1979.

31. Kirk-Othmer, "Aluminum and Aluminum Alloys", Encyclopedia of Chemical Technology, Vol. I, Second Edition, Interscience Publishers, New York, 1963, pp 929 - 990.

32. Kneen, T. and Strauss, W., "Deposition of Dust from Turbulent Gas Stream," Atmospheric Environmental, Vol. 3, 1969.

33. J. K. Koester, "Interaction of Slag Deposits with Alkali-Seeded Combustion Products, paper presented at The Engineering Foundation International Conference on 'Fouling of Heat Exchange Surface', 31 Oct - 5 Nov 1978.

34. Krupp, J., "Particle Adhesion, Theory, and Experiment," Advanced Colloid and Interface Science, 7, 1967.

35. A.K. Kulkarni, Y-J Wang and R.L. Webb "Fouling and Corrosion in Glass Furnace Regenerators", paper presented at the Engineering Foundation International Conference on 'Fouling of Heat Exchange Surface', 31 Oct - 5 Nov. 1982.

36. G. S. Lane, et al., Studies of In-Bed Corrosion in a Pressurized Fluidized Bed Combustor, Fluidized Combustion Contractors Limited Final Reprot, EPRI CS-1935, July 1981.

37. S.Y. Lee, "Optimum Dosage of Magnesium Additive for Combustion Turbines Burning Heavy Fuels," paper presented at the Engineering Foundation International Conference on 'Fouling of Heat Exchange Surface', 31 Oct - 5 Nov 1982.

38. D.J. Lees, "The Influence of Gas and Deposit Chemistry on the Fireside Corrosion of Furnace Wall Tubes in Coal-Fired Boilers", paper presented at the Engineering Foundation International Conference on 'Fouling of Heat Exchange Surface; 31 Oct - 5 Nov 1982.

39. Lin, S.M., "Particle Deposition Due to Thermal Force in a Tube," Applied Scientific Research, Vol. 32, 1976.

40. D. W. Locklin, et al. "Fireside Additive Trials in Utility Boilers Overview of an EPRI Survey". Paper 11a, presented at the American Power Conference, April 1979.

41. T. Lyman, (Editor) Metals Handbook, Vol 1 - Properties and Selection of Metals, 8th Edition, American Society for Metals, Novelty, Ohio, pp. 564 - 593.

42. W. J. Marner, An Assessment of Gas-Side Fouling in Cement Plants, JPL Pullication 82 - 83, DOE/ID-12138-2 (DOE Contract No. DE-AI07-80ID12138), September 1982.

43. Ladislav Novak, "Fouling in Plate Heat Exchangers and Its Reduction by Proper Design," Product Planning and Research, Alfa-Laval AB, Box 1721, S-221 01 Lund", Sweden. Presumed to be presented at the Engineering Foundation International Conference on 'Fouling of Heat Exchange Surface', 31 Oct - 5 Nov 1982.

45. N. B. Orr, "Report on Ljungstrom Regenerator project for Heat Recovery in the Aluminum Industry with Flue Gas Temperature up to 750°C, presented at the Energy Conservation R&D Meeting in Industrial Processes, Brussels, November 1978.

46. W. L. Pope, et al., "Heat Exchanger Design - "Why Guess a Design Fouling Factor when it can be Optimized?" LBL-7067, June 1978, Lawrence Burkeley Laboratory, University of California, Berkely, Ca., to be presented at The Energy Technology Conference and Exhibition in Houston, Tx., 5-7 November 1978.

47. Rouhiainin, P.O. and Stachiewicz, J.W., "On The Deposition of Small Particles From Turbulent Streams," Journal of Heat Transfer, ASME Tranactions, 1970.

48. Rumpf, H., "Particle Adhesion; Chapter 7," Agglomeration 77, 1977.

49. J. W. Suhausen, "High Temperature Heat Recovery", paper presented at the Symposium Application of Technical Knowledge to Conserve Industrial Fuels, November 1975.

50. J. Suhausen, "Reliability, Efficiency and Economics of Recuperators in Industrial Applications", paper presented at the 1981 International Gas Research Conference.

51. T. T. Semler, J. L. Bogue, and L. A. Casper, "Fouling Characteristics and Evaluation on a Finned-Tube Diesel Exhaust Gas Heat Recuperator", paper presented at the Engineering Foundation International Conference on Fouling of Heat Exchange Surface, 31 Oct.-5 Nov. 1982.

52. E. F. C. Somerscales and M. Kassemi, "Measurement of the Thermal Resistance of Corrosion Products", paper presented at the Engineering Foundation International Conference on Fouling of Heat Exchange Surface, 31 Oct.-5 Nov. 1982.

53. S. L. Soo, "Particle-Gas Surface Interaction in Collection Devices", International Journal of Multiphase Flow, Vol. 7, 1973.

54. R. C. Stoeffler, "Enhancement of Heat Transfer in Waste-Heat Exchangers", United Technologies Research Center Final Report R80-914653-15, (DOE Contract DE AC03-77-ET11348), July 1980.

55. R. C. Stoeffler, "Parametric Performance Studies on Fluidized Bed Heat Exchangers", United Technologies Research Center Report R82-915729-7 (DOE Contract No. DE-AC22-PC04280), January 1982.

56. M. A. Styricovich, et al, "Some Aspects of Heat Exchangers Surface Fouling Due to Suspended Particles Deposition", presented at the Engineering Foundation International Conference on Fouling of Heat Exchange Surface, 31 Oct.-5 Nov. 1982.

57. V. J. Tenney, "United States Ceramic Heat Exchange Technology - States and Opportunities", Oak Ridge National Laboratory 1982 paper, paper may have been presented at the Engineering Foundation International Conference on Fouling of Heat Exchange Surface, 31 Oct.-5 Nov. 1982.

58. D. G. Tipton, "Effect of Mechanical Cleaning on Seawater Corrosion of Candidate OTEC Heat Exchanger Materials - Part 1; Tests with M.A.N. Brushes", Report No. ANL/OTEC-BCM-013, Argonne National Laboratory, September 1980.

59. K. C. Tsao and C. O. Jen, "Coal-Ash Agglomeration Mechanism and its Application in High Temperature Cyclones", Separation Science and Technology, Vol. 15, No. 3, 1980.

60. K. C. Tsao and H. Tabrizi, "Coal-Ash Agglomeration Mechanism in a High Temperature Cyclones", ASME Paper No. 82-WA/HT-29, November 1982.

61. M. I. Vdovenko and A. B. Reznyakov, "Physics of Interaction Between Aerosols and Surfaces Part Which They Flow", Fluid Mechanics-Solviet Research, Vol. 5, No. 4, 1976.

62. C. L. Wagoner, S. J. Vecci, and G. B. Olson, "Fuel and Ash Characterization and its Effect on the Design of Industrial Boilers", Paper No. PGTP 78-26, presented at the American Power Conference, April 1978.

63. T. F. Wall, "Mineral Matter in Coal and the Thermal Performance of Large Boilers", Prog. Energy Combustion - Science, Vol. 5, No. 1-A, June 1978.

64. C. S. Wang, J. J. Deabor, and S. P. Lin, "Effect of Fluid Inertia on Particle Collection", Physical Fluids, Vol. 21, No. 12, 1978.

65. R. L. Webb, et al, "Heat Exchangers for Secondary Heat Recovery from Glass Plants", paper presented at the Engineering Foundation International Conference on Fouling of Heat Exchange Surface, 31 Oct.-5 Nov. 1982.

66. _______________, Positive Pressure Heat Exchanger Cleaning System Test Report - Brayton-Cycle Recovery System Characterization Program, Airesearch Manufacturing Company of California, Report No. 81-18259 (DOE Contract No. EC-77-C-03-1557), 15 October 1981.

67. J. R. Wynnyckyj and E. Rhodes, "Mechanisms of Furnace Fouling", Department of Chemical Engineering, University of Waterloo, Waterloo, Ontario, Canada, 1982 paper. Work funded by the Canadian Electrical Assoc.

68. A. D. Zimon, "Adhesion of Dust and Powder", 1969, Plenum Press, New York-London.

☆U.S. GOVERNMENT PRINTING OFFICE: 1983-746-081/2620