FINAL TECHNICAL REPORT

MATERIALS FOR INDUSTRIAL HEAT RECOVERY SYSTEMS

Task 1

IMPROVED MATERIALS AND OPERATION OF RECUPERATORS FOR ALUMINUM MELTING FURNACES

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List of Acronyms

CFD	Computational Fluid Dynamics
DOE-EERE	Department of Energy – Energy Efficiency and Renewable Energy
FE	Finite Element
IR	Infrared
OD	Outer diameter
ORNL	Oak Ridge National Laboratory
PLC	Programmable logic controller
R&D	Research and Development

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EXECUTIVE SUMMARY

Production of aluminum is a very energy intensive process which is increasingly more important in the USA. This project concentrated on the materials issues associated with recovery of energy from the flue gas stream in the secondary industry where scrap and recycled metal are melted in large furnaces using gas fired burners. Recuperators are one method used to transfer heat from the flue gas to the air intended for use in the gas burners. By preheating this combustion air, less fuel has to be used to raise the gas temperature to the desired level. Recuperators have been successfully used to preheat the air, however, in many cases the metallic recuperator tubes have a relatively limited lifetime – 6 to 9 months. The intent of this project was to determine the cause of the rapid tube degradation and then to recommend alternative materials or operating conditions to prolong life of the recuperator tubes.

The first step to understanding degradation of the tubes was to examine exposed tubes to identify the corrosion products. Analyses of the surface scales showed primarily iron oxides rather than chromium oxide suggesting the tubes were probably cycled to relatively high temperatures to the extent that cycling and subsequent oxide spalling reduced the surface concentration of chromium below a critical level.

To characterize the temperatures reached by the tubes, thermocouples were mounted on selected tubes and the temperatures measured. During the several hour furnace cycle, tube temperatures well above 1000°C were regularly recorded and, on some occasions, temperatures of more than 1100°C were measured. Further temperature characterization was done with an infrared camera, and this camera clearly showed the variations in temperature across the first row of tubes in the four recuperator modules.

Computational fluid dynamics was used to model the flow of combustion air in the tubes and the flue gas around the outside of the tubes. This modeling showed the distribution of air in the tubes was not at all uniform, and it was strongly affected by velocity and the turbulence created by items in the lower plenum such as the fork lift slots, structural members, and broken spiral fins originally intended to promote non-linear flow in the tubes.

Finite element modeling of the stresses developed between tubes in the first and second rows showed how stresses could become large enough to account for the bending and bowing of tubes in the first row.

To prevent rapid degradation and subsequently short lifetimes of recuperator tubes two approaches were offered. Alloys that form an aluminum oxide surface layer would be more likely to survive the excursions to very high temperatures. However, availability of these alloys in the tube sizes required might be an issue as might the ability of welding these alloys to the other recuperator components.

The other approach would entail improving the design of the recuperator module and to change operating procedures to avoid conditions where very hot flue gases are flowing across the recuperator tubes at times when reduced combustion air is flowing through the recuperator tubes.

INTRODUCTION

The melting furnaces used in the secondary aluminum industry consume a significant amount of energy to melt the aluminum charge. The heat is produced by burning a fossil fuel, usually natural gas. In order to improve the furnace's energy efficiency, the exhaust gas from the furnaces is used to preheat the air used in the combustion process. A number of heat exchanger designs are available for preheating the combustion air; this study has addressed materials issues associated with the recuperator design. Experience has shown that lifetimes of recuperator tubes in the highest temperature locations are often in the 6 to 9 month range. In order to improve the lifetime of these tubes and, consequently, improve the economic justification for using recuperators, this study was undertaken to characterize both the tube degradation and the environment encountered by the tubes and then to identify alternate materials or operating procedures that would extend the life of the tubes. The objective is to extend the life of recuperator tubes five-fold by substituting alternate tube materials in existing recuperators and improving recuperator design and operating practices, and thus increase their use in a larger fraction of aluminum melters. This in turn would reduce the energy intensity of the secondary aluminum melting industry which is the primary objective of DOE-EERE's Industrial Technology Program.

To accomplish this objective, Task 1 of the Project (the other tasks focused on recovery boilers used in the pulp and paper industry) was originally divided into the following subtasks:

- 1) characterize the tube degradation;
- 2) characterize the chemical, thermal and mechanical environments;
- 3) characterize the materials used;
- 4) perform thermodynamic and stress modeling of the recuperators;
- 5) conduct laboratory corrosion studies in simulated environments;
- 6) identify alternate tube and refractory materials;
- 7) expose the recommended materials in a recuperator; and
- 8) recommend the best alternative materials and operational changes.

It was originally expected that several aluminum companies would participate in this project, but only Logan Aluminum of Russellville, Kentucky, was identified by Secat as being interested and available to participate. The study began with Logan Aluminum as the key participant, but significant budget cuts were imposed, so the subtasks were revised. A subtask was added to assess the interest in heat recovery in the aluminum industry, to assess the different methods available and to identify the companies and their capabilities and experience. The subtasks to conduct laboratory corrosion studies and to expose recommended materials in the recuperator were dropped.

The subtask to assess the industry-wide interest in heat recovery, identify the different methods available, and identify the companies and their capabilities was undertaken by E3M Inc. The effort to characterize degraded tubes was carried out at ORNL and SECAT while the environment characterization was a joint effort between ORNL and Logan Aluminum. The modeling work was conducted at ORNL, and the recommendations on operational changes came about as a result of discussions between personnel at Logan Aluminum and ORNL.

ASSESSMENT OF HEAT RECOVERY NEED AND RECUPERATOR USE IN THE ALUMINUM INDUSTRY

Heat recovery is an essential energy-saving part of aluminum melting processes. Enhancing heat recovery in aluminum melting furnaces and other heating processes used by the aluminum industry is a direct and very efficient way to substantially improve energy utilization and lessen environmental impact. Performance of heat recovery systems (recuperators) in aluminum melting furnaces depends on several factors such as flue gas temperatures, requirements for duty cycle, composition of furnace flue gases (presence of O₂ and/or combustibles such as CO, H₂, unburned hydrocarbons etc.), presence of particulates and gaseous contaminants, and furnace operating practices. Proper selection of materials for heat recovery systems is complex, yet crucial for satisfactory performance.

For this subtask, the current trends in heat recovery systems have been evaluated, major suppliers of heat recovery systems have been contacted, and past, present, and future trends in application of heat recovery system in aluminum melting furnaces, design and application related issues and use of advanced materials for heat recovery systems have been evaluated.

Results of these activities clearly indicate that significant energy savings could be realized from selection of proper materials and material improvements. However, current suppliers of recuperators are not very optimistic about the future use of conventional recuperator designs on medium to small size melting furnaces used by many secondary aluminum plants. The aluminum industry is more inclined to use relatively new heat recovery technology (regenerative burners) that include a regenerative heat recovery system integrated with the burners. However only a few companies are installing regenerative heat recovery systems on existing furnaces that represent more than 65% to 75% of the operating capacity expected to exist in USA. Major barriers to using regenerative burners are: cost of equipment and installation for retrofit applications, floor space requirements, added maintenance, and lack of flexibility in furnace heating system design (location of burners and flue gas discharge).

The recuperators associated with aluminum melting furnaces utilize hot flue gas to preheat the combustion air for the burners that provide the heat to melt the aluminum. The heat transfer surfaces used in the recuperators are exposed to high temperature and often corrosive flue gas on the outside while ambient temperature air is fed into the tubes. These tubes have a relatively short lifetime that averages only a few months on the leading side of the recuperator, where bending, warping and thinning occur.

The activities conducted as part of this subtask included:

- 1) Assessment of aluminum melting processes and systems used by the U.S. industry. This activity included collection of information on common operating practices, energy requirements, and issues related to efficiency improvement.
- 2) Investigations in characteristics of flue gases from aluminum melting furnaces
- 3) Review of flue gas heat recovery systems and energy savings - efficiency improvement with use of combustion air preheating.
- 4) Contacts with suppliers of commonly used recuperators and other heat recovery systems to assess current and future trends in design and application of these systems in aluminum industry.

Assessment Of Aluminum Melting Processes And Systems Used By The U.S. Industry

Melting of aluminum is a very energy intensive process and often represents the largest percentage of total energy used in secondary aluminum plants. These furnaces use recycled/scrap material and virgin material as charge and produce molten metal that is cast in various shapes and sizes.

A large (>75%) percentage of total aluminum melting in the secondary aluminum industry uses natural gas as source of heat for melting. Commonly used aluminum alloys melt at about 678°C (1250°F) and are “poured” at 29 to 56°C (50 to 100°F) above the melting point. Heat content of commonly used molten aluminum metal is approximately 430 Btu/lb. However, in practical applications the flue gases from an aluminum melter can be in the range of 1038 to as high as 1204°C (1900 to 2200°F) resulting in very large amount of energy content for the melting furnace flue gases. Energy supply and distribution for a typical aluminum melting furnace is shown in Fig. 1. In many cases, flue gases contain 50% to 70% of the total furnace heat input while average thermal efficiency, defined as the heat delivered to molten aluminum to total heat input for the furnace, for gas fired aluminum melting systems is approximately 23%. Thus the flue gases may contain 2 to 2.5 times the heat delivered to the aluminum. In addition to heat losses in the flue gases, the melter has additional losses through insulated walls, radiation losses and other losses that may account for 5% to 10% of the total heat input.

Figure 1 Energy supply and distribution for a typical aluminum melting furnace

Furnace thermal efficiency can be increased by reducing flue gas heat or by recovering part of the heat that can be used for the melting process itself. Currently two methods are in use by the industry for recovering part of the flue gas heat. The following methods can be used to recover the flue gas heat.

- Combustion air preheating by using flue gas heat
- Load or charge preheating by using flue gas heat, prior to load charging in the furnace.

Details of these methods are discussed later.

Investigation of Characteristics of Flue Gases from Aluminum Melting Furnaces

Performance and overall economics of a heat recovery device whether it is used for combustion air preheating or charge preheating depends on the nature of flue gases passing through the heat recovery device. During this program, E3M contacted several aluminum companies to investigate characteristics of flue gases discharged from commonly used aluminum melting furnaces. Details are presented in the Appendix.

A summary of findings is given below.

- a) Gases are at a very high temperature, usually in the range of 871 to 1204°C (1600 to 2200°F). Although aluminum melts at less than 704°C (1300°F) and the molten metal is tapped or poured at less than 760°C (1400°F), the furnace set point that affects heat transfer within the furnace and production rate of the furnace is usually set between 816 and 927°C (1500 and 1700°F). A higher furnace temperature set point results in flue gas temperatures in the range of 982 to as high as 1093°C (1800 to 2000°F). These temperatures are considered very high for available materials, and it is uneconomical to use a recuperator that can accept such high temperature. Hence, in almost all cases these gases are mixed with cold ambient air to drop flue gas temperature below 927°C (1700°F). An automatic temperature control system is used to control the amount of air introduced as cooling air. Such a system is very useful in reducing maintenance of a recuperator and extending its life. However such a system has one major draw back. It works satisfactorily as long as the flue gases discharged from a furnace do not contain any combustibles such as CO, H₂ or unburned hydrocarbons. Such combustible gases could be present in flue gases when the combustion control system for burners is not adjusted properly or when the burner firing rate is so high that combustion cannot be completed within the furnace space. In such cases the cooling air actually acts as combustion air, releasing more heat in flue gases rather than cooling the gases. This results in a rise in flue gas temperature rather than a drop in temperature. These hot gases, in turn, raise the recuperator tube temperature, in many cases, above their safe operating limit, resulting in premature failure of recuperator parts.
- b) Presence of fluxing agents (chlorine, fluorine, etc.)
Aluminum melting furnaces frequently use fluxing agents that are highly corrosive. The actual composition depends on the alloy composition and final product specifications. However, in each case use of fluxing agents introduce highly corrosive elements such as chlorine, fluorine, etc. that promote degradation of the recuperator material. Chemical reactions between the corrosive gases and metal tubes result in extremely short life for the recuperator components. Use of any type of “exotic” materials that would extend the recuperator life is uneconomical.
- c) Presence of particulates (aluminum, aluminum oxide, magnesium, manganese, etc.)
During the aluminum melting process a small percentage of the charge material is oxidized due to the presence of oxidizing agents such as O₂, CO₂ and H₂O in combustion products. The oxides include aluminum oxide, magnesium oxide, iron oxide, etc. In many cases the oxides are in the form of fine particles that are entrained in flue gases and are discharged from the furnace with flue gases. These particulates, often in very fine size, deposit on recuperator surfaces and at high temperature, react with metallic (or non-metallic) materials.

The net effect of these reactions is shorter life of recuperator parts and often, premature failure of metal at critical locations.

d) Presence of combustibles (CO, H₂, hydrocarbons, etc.)

As mentioned above, the presence of combustible materials in flue gases could result in higher than design temperatures for recuperators when dilution or cooling air is added to flue gases. In cases where no cooling or dilution air is used, the presence of combustible materials still presents severe problems for the recuperator. The combustible materials may include soot that deposits on heat transfer surfaces and reacts with metal. The combustible gases in the presence of other constituents may accelerate detrimental reactions that affect the recuperator life. In a few cases, small air leaks from higher-pressure combustion air result in combustion of gases producing localized hot spots on the recuperator surfaces leading to shortened life of recuperator components.

e) Presence of combustible volatiles from coated scrap charge material

The aluminum melting furnace charge or load consists of scrap obtained from a variety of sources. In many cases, even after use of separation processing of scrap, the scrap includes combustible materials such as paint, paper, plastic, rubber etc. This material usually burns and generates combustion products. However, in some cases where there is poor distribution of heat or insufficient time for combustion, these materials, products of incomplete combustion, or inorganic materials end up in the flue gases discharged from a furnace. These materials or vapors have the same effects as combustible materials as described above.

f) Variations in flow, temperature and composition of gases

Almost all aluminum melting furnaces are operated in semi-batch fashion. The cold charge is introduced in the furnace at a certain frequency, varying from every few minutes to as long as 2 hours for each batch of the load. This results in variations in temperature, flow, and composition of flue gases leaving the furnace. Variations in flue gases could result in cycling of metal temperature for a recuperator and thermal fatigue for the metal used in the recuperator. Thermal fatigue would reduce life of the recuperator materials. Additionally, these variations could result in cyclic thermal expansion and premature failure of welds or other areas of metal joining within the recuperator. Failed welds or joints could result in air leakage from the higher pressure combustion side to the flue gas side and affect metal gas reaction or gas-gas reaction within the recuperator on the flue gas side. This could also change the air-fuel ratio for the burner and result into sub-stoichiometric combustion that would form combustible gases or soot in the flue gases.

Review of Flue Gas Heat Recovery Systems and Energy Savings - Efficiency Improvement with Use of Combustion Air Preheating

As mentioned previously, aluminum melting furnace thermal efficiency can be increased by reducing flue gas heat or by recovering part of the heat that can be used for the melting process itself.

Currently two methods are in use by the industry for recovering part of the flue gas heat.

- Combustion air preheating by using flue gas heat in a recuperator or a regenerative burner system
- Load or charge preheating by using flue gas heat, prior to load charging in the furnace.

Combustion air preheating by using flue gas heat is more commonly used than charge preheating. Potential savings by combustion preheating depends on two major parameters: flue gas temperature and rise in combustion air temperature or effectiveness of the air preheater used.

Table 1. Fuel savings with use of preheated combustion air using flue gas heat recovery

Fuel savings given in percentages of current fuel input						
Exhaust Temperature °F (°C)	Combustion Air Temperature °F (°C)					
	600 (316)	800 (427)	1,000 (538)	1,200 (649)	1,400 (760)	1,600 (871)
1,000 (538)	13	18	—	—	—	—
1,200 (649)	14	19	23	—	—	—
1,400 (760)	15	20	24	28	—	—
1,600 (871)	17	22	26	30	<u>34</u>	<u>—</u>
<u>1,800 (982)</u>	18	24	28	33	<u>37</u>	<u>40</u>
<u>2,000 (1093)</u>	20	26	31	35	<u>39</u>	<u>43</u>
2,200 (1204)	23	29	34	39	43	47
2,400 (1316)	26	32	38	43	47	51

Table 1 can be used to estimate fuel savings by using flue gas heat to preheat combustion air used in the melting furnaces. The bold values for flue gas temperature and air preheat temperature are practically possible conditions for aluminum melting furnaces when an external air preheater is used. Note that the flue gases may exit a furnace at much higher temperature than the furnace ‘set point’ temperature and in almost all cases they need to be cooled if the flue gas temperature is higher than approximately 871°C (1600°F). This is due to limitations on allowable surface temperature for flue gases entering the air preheating equipment.

Flue gas heat recovery – combustion air preheating by using flue gas heat in a recuperator

The most commonly used combustion air preheating arrangement, commonly known as a recuperator system, for aluminum melting furnaces is shown in Fig. 2. In this case flue gases or combustion products from a furnace are directed to an air preheater. In almost all cases where a recuperator is used, the flue gas temperature from an aluminum melting furnace is too high for the materials used in the air preheater device and it is necessary to “temper” the flue gases and bring them down to a temperature of about 871°C (1600°F) or lower prior to their introduction to the air preheater device. At this time the economics (capital cost vs. savings) of flue gas heat recovery for combustion air preheating allow 40% to 60% heat recovery.

The industry uses several designs of recuperators; however, they can be broadly divided into two categories: convective recuperators and radiation recuperators.

Convection recuperators use thermal convection as a primary mode of heat transfer on the flue gas side as well as the combustion air side. A typical convection recuperator design includes a number of tubes. Combustion air or flue gases pass through the tubes and other gases (flue gases or combustion air respectively) flow over the tubes. Heat is transferred from flue gases to the tubes and then from tube surfaces to combustion air. Flow of flue gases and air can be parallel

(in the same direction) or counter flow (cold air enters the area where cooled flue gases are discharged and hot flue gases enter the area where hot air is discharged to burners) or cross flow (flue gases or combustion air flows in the cross wise direction – 90° – to the combustion air or flue gases respectively). This basic design is offered in many varieties. The cross flow design commonly used for aluminum melting furnaces in the US is shown in Figs. 3 and 4.

Figure 2 Typical recuperator installation used for preheating combustion air

Figure 3 Example of a cross-flow recuperator system

Figure 4 Commercial cross flow recuperator used for aluminum melting furnaces

The radiation recuperator design is based on the use of thermal radiation from high temperature flue gases containing CO_2 and H_2O to preheat combustion air. In this case flue gases pass through a metallic stack that is surrounded by the flowing combustion air. Heat transfer on the flue gas side is by thermal radiation while it is by convection on the combustion air side. This design is most suitable for furnaces that discharge flue gases above 760°C (1400°F) and use relatively large stacks, usually larger than 1.2 m (4 ft) in diameter.

Major advantages of this design include much lower pressure drop on the flue gas side, absence of large surface areas (such as tubes) in flue gas passages and much less problem with plugging of flue gas passages.

A typical configuration for radiation recuperator is shown in Fig. 5. It should be noted that very few aluminum melting furnaces in the US use radiation type recuperators.

Figure 5 Example of a radiation type recuperator

During the last 30 years the aluminum industry has gone through a cycle of adapting and rejecting use of recuperators. Prior to the 1970s, very few installations used any type of flue gas heat recovery systems due to relatively low energy prices. However, in the early 1980s with an escalation in energy prices, many companies investigated and adapted use of conventional recuperators, such as shown in Fig. 5, to reduce energy use in melting furnaces. Within a short time, 3 to 5 years, the installations experienced severe maintenance and operational problems and the economics of using recuperators became very questionable. Many companies abandoned use of recuperators and operated the furnaces without recuperators or any other type of combustion air preheating devices. Major issues related to use of recuperators include:

- Higher pressure drop on flue gas side resulting in positive pressure in furnaces and hot gas leaks from furnace openings
- Plugging of passages in recuperators
- Leaks in tubes resulting in loss of burner combustion control
- Tube burn-outs due to high tube temperatures at certain locations
- Corrosion of tube materials that eventually results in tube failure
- Deformation of tubes that causes severe problems in maintenance or repair of the tubes
- Unreliable operation due to above mentioned factors

In addition to this, several operating practices, particularly the push for getting higher production than the design capacity, result in additional problems. Most companies drive their furnaces hard to get 5% to 10% higher production and that results in higher flue gas temperatures and severe damage to a recuperator. Push for higher production has resulted in higher input, higher flue gas temperatures (sometime far above the material design limitations) and often inefficient combustion that increases fuel consumption by a significant amount (10% to 20%), wiping out the expected benefit from use of recuperators. The companies often neglect maintenance on recuperators and the result is even more fuel consumption in furnaces.

Flue gas heat recovery – combustion air preheating by using flue gas heat in a regenerative burner system

A new concept for flue gas heat recovery has been developed and applied in limited installations during the last 10 years. In this concept a regenerative system in which a pair of burners with integral heat storage medium is used to preheat combustion air. A typical system is shown in Fig. 6. In this system two burners (A and B) are installed on a furnace. Each burner includes a heat storage device such as packed ceramic spheres. The burners are fired alternatively. For example, during cycle 1 in Fig. 6, burner A is fired while burner B is used to exhaust flue gases, primarily from burner A. The hot gases pass over a heat storage medium and deliver heat to the heat storage medium cooling the flue gases while heating the medium. After a short duration (15 to 20 seconds) the flow is reversed. Now during cycle 2, burner B is fired and it receives its combustion air that has been passed over the hot heat storage medium, bringing it to a very high temperature, often 60% to 80% of the flue gas temperature. The heat storage medium associated with burner B cools down while burner B is fired with highly preheated combustion air. During this time burner A is used to exhaust flue gases generated in burner B. The cycling of burners continues resulting in a very high degree of heat recovery from furnace flue gases.

Figure 6 Example of a regenerative burner system used on aluminum melters

A regenerative burner system has an efficiency of 72% to 75% and delivers combustion air at about 760 to 816°C (1400 to 1500°F). This can reduce fuel consumption by 40% while the use of recuperators reduces fuel consumption by about 30%. This difference is significant when one also considers the effect of this on a possible increase in production or melt rate.

The regenerative (regen) burners do present problems related to plugging of the bed when the furnaces are operated with dirty scrap, generate high percentage dross and generate soot particles. The problem is more severe during fluxing, however an automatic control of the system allows bypassing of the regenerative system when the user performs batch fluxing. Continuous fluxing, rarely used, could present a problem if the fluxes are highly corrosive to the ceramic materials.

It is necessary to clean the bed to avoid degradation of performance and reduction in firing rate that in turn would result in a drop in melt rate and production. It is necessary to change the bed when it “plugs up”. A bed would remain clean for several months if the furnace operation is charged with clean charge material. However, most users would charge some type of purchased scrap that may contain impurities. In this case it is necessary to change the bed periodically – ranging from once a week to once a month. Changeover of the bed requires approximately ½ hour during which time the furnace continues to run using bypass dampers and cold air. The end effect is loss of efficiency during this time. The bed needs to be cooled and cleaned with a water spray which may take one shift or longer. In most companies a spare bed is maintained to replace a plugged bed while one of the beds is being cleaned and kept ready for the next changeover. There is very little, if any, attrition of the ceramic balls that are made out of alumina. The bed container is a stainless steel box that is lined with insulation. The balls are supported on carbon steel or stainless steel supports.

The entire regenerative system includes regenerative bed, burners, associated valves, linkages, and furnace temperature controls. The system uses a fairly complex (compared to simple burner-recuperator system) control system to maintain the heat recovery and continuing efficient operation. The cost of this system compared to cold air burner is almost 3 times, and the cost is 1.5 times the cost of recuperative systems. However the life cycle cost analysis and payback period analysis at today’s energy prices (\$7 to \$10 per MM Btu) can easily justify the higher initial cost. The simple payback period is usually less than one year and it is significantly lower if one considers the value of increased production related economics.

Flue gas heat recovery – load or charge preheating by using flue gas heat

In a typical charge preheating system, flue gases from a furnace are used to preheat the charge material in a separate preheater device or in an extension of the furnace charge system. In either case, the charge material is typically heated to a temperature of at least 260°C (500°F), and possibly as high as 427°C (800°F), before it is charged manually or by a conveyor system. The preheating process also allows removal of moisture and volatile organic compounds in the charge material.

Depending on the charge material content and its composition, it may be necessary to use an emission control devise. Use of a charge preheater is not very common in the US. However, they are extensively used in other parts of the world such as Japan, Europe, India, China, etc. In the US most of the charge material is heated in a separate charge dryer with the intention of removing moisture from the charge. Charge preheating offers 20% to as high as 35% energy savings if it is done by using heat from flue gases.

Since the present program addresses recuperators and other types of combustion air preheating systems, issues related to charge preheating were not investigated further. A summary of the information acquired from contacts with suppliers of recuperators and other heat recovery systems is given in the Appendix.

CHARACTERIZATION OF RECUPERATOR TUBE DEGRADATION

The recuperators or heat exchangers used on aluminum melting furnaces are intended to capture a significant amount of heat from the flue gas leaving the furnace. There are a number of recuperator manufacturers and a variety of designs but they all employ fairly large diameter tubes (3-4 inches OD) oriented vertically so that the hot flue gas passes over the outside of the tubes and the combustion air flows through the inside of the tubes. The tube arrangement might vary from one installation to another, but for the recuperators studied at this particular mill, modules or bundles containing 100 tubes each are used. A picture of one module is shown in Fig. 7, and a sketch showing the tube arrangement and gas flow pattern is shown in Fig. 8. As shown in Fig. 7, the 100 tubes are arranged in 5 rows that each contained 20 tubes, and the tubes are positioned in a rectangular array rather than in a more densely packed, triangular array. Each furnace at this location uses three or four recuperator modules, and generally the gas flow is as shown in Fig. 8. However, in a few cases, the flow of combustion air has been reversed in an attempt to provide additional cooling to the first row of tubes. The first two rows of tubes encounter the hottest gases coming from the furnace, and these tubes are fabricated from Alloy HE while the tubes in the remaining 18 rows are fabricated from Alloy HD.

A schematic drawing of the furnace and recuperator arrangement is shown in Fig. 9, and there are a few features worthy of particular emphasis. A refractory lined duct carries the exhaust gases from the furnace to the recuperator modules and then, eventually, to a stack where the gases are vented. To avoid radiant heating of the recuperator tubes, the duct has an approximately 90° bend so that the tubes are out of direct line-of-sight of the furnace. In addition, the drawing shows locations on opposite sides of the duct where dilution air can be

Figure 7 Previously exposed recuperator module showing 20 rows with 5 tubes in each row. Note bent and broken tubes in the first row and Missing refractory on the upper end of the tubes.

Figure 8 Sketch showing tube arrangement and gas flow in recuperator module

Figure 9 Sketch showing the furnace and recuperator arrangement.

injected into the duct. Not shown in the drawing is a nozzle that can be used to spray water into the duct to provide additional cooling of the exhaust gases. The temperature of the exhaust gas coming from the furnace has been estimated to be in the vicinity of 1200°C during the period when the furnace is hottest. Consequently, both dilution air and the water spray are needed to lower the temperature of the gases coming from the furnace to a range that is tolerable for the recuperator tubes. Nevertheless, severe degradation of the tubes occurs in the form of wall thinning, cracking and bending.

Several approaches have been tried to promote turbulence/mixing of the exhaust gas. Specifically, in one furnace, a row of uncooled tubes was suspended just in front of the recuperator tube modules to disturb the gas flow. In another approach, brick columns were reportedly constructed in the duct as an alternate means of disrupting the gas flow.

It has been suggested that injection of the dilution air might have other less beneficial consequences. If the burners used for heating the furnace are operated so there is excess fuel, those combustible vapors could be carried into the exhaust duct where, upon mixing with the dilution air with its normal oxygen content, they could burn near the surface of the recuperator tubes.

Another possibility for recuperator tubes reaching unexpectedly high temperatures could occur during the period when the furnace burners are turned down or off. This situation would greatly reduce or totally eliminate the need for pre-heated combustion air. Consequently, if no air flows through the recuperator tubes but hot exhaust gases from the furnace continue to flow through the duct, the temperature of the recuperator tubes could approach the temperature of the exhaust gases.

These are two, but by no means all, of the scenarios that provide possible explanations for the development of high tube temperatures that could result in the degradation actually seen. Some other possibilities have been discussed in the previous section.

Experimental Approach

The goal of this task was to determine the degradation mechanism operating on the recuperator tubes and to identify alternate alloys and/or changes in operating practices that would lead to longer tube life. The approach selected was to characterize the degradation of the tubes by examining failed tubes and to define the environment to which the outer surfaces of the tubes are exposed. The environment characterization was accomplished by using thermocouples attached to the tubes to measure the surface temperatures of the tubes and by using an infrared (IR) camera to define the temperature variations across all the tubes. The information obtained from these measurements as well as some operating results provided input for finite element (FE) and computational fluid dynamics (CFD) modeling. The FE modeling addressed the stresses that develop in the recuperator tubes as a result of heat being applied primarily to one side. The objective was to determine if bending of the front row of tubes out of the normal plane could be explained by the presence of these stresses at elevated temperature. The CFD modeling was used to study the flow of combustion air through the recuperator tubes and exhaust gas around the same tubes. The CFD study addressed the distribution of air as it flows through different parts of the module, and it considered the effect of flow restrictions in the bottom plenum of the module. As a result of these studies, several conclusions can be drawn regarding possible means to slow the degradation of the recuperator tubes.

Examination of recuperator tubes

A number of examinations have been conducted on badly degraded recuperator tubes and on scale removed from these tubes. One problem with getting samples of these tubes for examination is the fact that the modules are generally stored outside once they are removed from the furnace. This means that any water soluble corrosion products will be washed away as soon as the modules are exposed to the first rainfall. All the tube samples collected had been exposed to the weather, but one set of scale samples was collected before the recuperator modules were moved outside where they would be exposed.

A number of scale samples were analyzed using x-ray diffraction to identify the phases present in the scale. In some samples the scale was tested in the as-received condition, and results from these samples are only qualitative in nature. Preferential orientation of grains in an as-received sample will result in some diffraction peaks being unusually intense while others have reduced intensity. X-ray patterns taken from ground samples will give results that will be at least semi-quantitative in nature. An example of the results for a ground sample are shown in Fig. 10 which is from scale removed from the OD of an exposed recuperator tube. As shown in Fig. 10a, the primary components are oxides of iron, Fe_2O_3 and Fe_3O_4 . On the pattern in Fig. 10b, the scale is expanded so that some of the smaller peaks are revealed. This shows that a very small amount of $\text{Ni}(\text{ClO}_4)_2$ is also present on the surface of the sample.

Recuperator tube samples were analyzed at Secat and ORNL. A section examined at Secat was taken from a front row tube that showed significant thinning, while both unexposed and exposed tube samples were examined at ORNL. The section examined at Secat was taken from the area shown on the left in Fig. 11, and the actual sample is shown on the right in the same figure. Light micrographs of cross-sections of the tube show areas of deep pitting and severe thinning in Fig. 12, and similar features of extensive corrosion are shown in the scanning electron micrograph in Fig. 13. A micrograph of the etched cross section is shown in Fig. 14, and this shows microstructural features indicating segregation that could account for the brittle characteristic of the exposed material at room temperature. Chemical analysis of scale samples

showed very little or no evidence of chlorine, but appreciable sulfur content was found in a few of the scale samples.

(a)

(b)

Figure 10 X-ray diffraction patterns for powdered scale from an exposed recuperator tube. The major peaks are shown in (a) while the minor peaks are more easily seen in (b).

The exposed tube section examined at ORNL is shown in Fig. 15. The overall picture gives some indication of the deformation of the tube while the close-up shows the large hole that developed as a result of through-wall corrosion. To determine the extent of thinning, wall thickness measurements were made at 8 positions around the circumference of the tube and at 14 positions along the axis of the tube. The results are displayed in Fig. 16 in two ways; thickness versus position along the axis of the tube and thickness versus position around the circumference

Figure 11 Area of recuperator from which sample was removed (left) and actual sample that was used in the examination (right).

Figure 12 Micrographs of cross-sections of recuperator tubes showing areas with deep pitting and severe thinning

Figure 13 Scanning electron micrograph showing extensive corrosion of the tube

Figure 14 Micrograph of the etched cross-section of the tube showing segregation that could contribute to the brittle room temperature behavior of the tube

Figure 15 Exposed tube sample examined at Oak Ridge National Laboratory

Figure 16 Wall thickness measurements (vertical axis in inches) for exposed tube as a function of position along the length of the tube (upper plot) and as a function of position around the tube (lower plot).

of the tube. These plots show the thinning was most extensive around positions 6-8 along the axis and at 0 and 180°. Cross-sections of the tube were taken at selected locations, some of

which (2, 3, and 4) are shown in Fig. 17. Examination of the cross-sections shows significant wall thinning with a thick oxide layer on the internal surface of the cast tube in Fig. 18. Higher magnification views of the thinner areas in Fig. 19 show the internal pores are elongated in the thinner areas suggesting significant plastic deformation has occurred in these areas. For comparison, an unexposed tube was sectioned and examined microscopically. The micrographs of this tube in Fig. 20 show the full thickness of the tube with some porosity that appears to be concentrated toward the ID of the tube. The severe thinning as well as the plastic deformation indicate the tubes were exposed to excessively high temperatures that resulted in severe wall thinning to the extent that the yield strength was exceeded. Information provided by the engineers responsible for the recuperators as well as x-ray fluorescence measurements of exposed tubes indicate the first row of tubes is fabricated of the cast, heat resistant austenitic alloy HE which nominally contains 28% chromium and 9% nickel.

Based on the examination of exposed tubes, it appears the tube material, which is intended for high temperature service, nevertheless experienced temperatures well in excess of the intended use temperature. In addition, the heating was not uniform which resulted in more rapid formation of oxide in some areas. Since it appeared that excessive temperatures were involved, it was decided to try to measure the actual temperatures reached by the tubes.

Figure 17 Location from which samples 2, 3 and 4 were taken.

Figure 18 Cross-sections showing significant wall thinning and thick internal oxide.

Figure 19 Higher magnification views of the thinner areas showing elongated pores suggesting significant plastic deformation

Figure 20 Unetched and etched views of unexposed tube.

Temperature measurements

Two approaches were used to try to determine the tube temperatures. One approach involved attaching thermocouples at selected positions on alternate tubes in order to get an indication of the maximum temperature and the temperature variation across the front row of recuperator tubes. A second approach involved using an infrared camera along with a limited number of thermocouples at selected locations.

The first effort at thermocouple measurements was done in a smaller furnace that utilized three recuperator modules (for a total of 15 tubes in the front row). At the time this thermocouple installation was made, a row of uncooled tubes was suspended in front of the actual recuperator tubes in an attempt to promote mixing, and the thermocouples were actually attached to these uncooled tubes. The planned locations for thermocouples on the different tubes are shown schematically in Fig. 21. Figure 22 shows the thermocouples after the installation was completed. The thermocouples were held in place by metal strips that were welded to the tubes, and some of those strips are visible in Fig. 22. Once the thermocouples were attached, the tubes were rotated 180° so that the thermocouples were actually on the “back side” of the uncooled

tubes. Based on results of the examination of the exposed tube sections, it would seem likely that the temperatures measured on the back side of the tubes might be appreciably lower than the “front” side temperatures. However, the tubes that were examined were air cooled while the tubes to which the thermocouples were attached did not have any cooling.

Two of the sixteen thermocouples were damaged during installation, but the remaining fourteen provided data for awhile. One “snapshot” view of the temperatures across the three modules is shown in Fig. 23. For this particular period, the highest temperatures were measured in the upper left corner and at the bottom center of the tube array. Temperature data were collected from these thermocouples for several weeks, and these data were plotted as a function of time on a daily basis. Two examples of these data are shown in Figs. 24 and 25. In Fig. 24, the furnace operated on a fairly regular cycle, and maximum temperatures reached a little over 1000°C. On a subsequent day with less regular operation (Fig. 25), the inlet flue temperature exceeded 1200°C. The measured tube temperatures were somewhat lower, but it should be noted that these were temperatures on the “back” side of the tubes. It would be expected that the “front” side of the tubes were likely somewhere between the measured flue temperature and the tube temperature. In any case, as with the exposed tubes that were examined, it is evident that the tubes periodically reached very high temperatures.

Although some interesting data were obtained from the thermocouple array, there were many areas of the recuperators from which no information was available. Consequently, it was proposed that some temperature measurement technology be borrowed from the paper industry. Specifically, IR cameras are used to observe what is occurring in boilers, particularly recovery boilers, in the pulp and paper industry. These cameras are designed so they can be mounted at an observation or air port, and they provide valuable information about activities in the boiler.

Figure 21 Planned thermocouple locations

Figure 22 Thermocouples after installation. Note that tubes were rotated 180° before startup.

Figure 23 Measured temperatures are shown for one of the hotter periods in the furnace. Note the hottest spots are in the upper left and the bottom center.

One of the companies that furnish IR cameras to the paper industry, Syn Fab, was contacted and they offered to provide a technician and a camera for a demonstration. In order to provide some cross-check of the IR camera measurements, several thermocouples were attached to the recuperator tubes. In order to provide a near-term opportunity to evaluate the IR camera, it was decided to conduct the tests in a different furnace at Logan Aluminum. The alternate furnace that was available was larger and, consequently, had four recuperator modules. In order to provide access for the IR camera, a hole was made in a door that had direct view of the recuperator tubes. The equivalent location is indicated in Fig. 9, and Fig. 26 shows the IR camera actually in position for viewing the recuperator tubes. In order to protect the camera from the intense heat of the furnace, a long, air-cooled tube extended from the camera lens through the wall of the furnace's flue duct. This proved to be a satisfactory arrangement for viewing the tubes.

During the initial studies with the IR camera, temperatures measured with the camera were compared with readings from the thermocouples. The equipment associated with the IR camera permitted the operator to select points in the area being viewed, and then the temperature of those points would be displayed. In addition, the area viewed by the IR camera was displayed on a monitor, and the color of the display provided an indication of the temperature. Figure 27a-d show the monitor display at four different times as the temperature of the flue gas, and consequently the recuperator tubes, increases. These displays show the 20 tubes that are in the four modules - five tubes in the front row of each module. There are several things worth noting in these figures. From the change in color, it is apparent how the tube temperature increases with time. However, the heating is not evenly centered. The module on the far right (#4) shows color changes before the tubes in the module on the left (#1). In fact, in the first three displays, the tubes in the leftmost module are barely visible. There are a couple of tube alignment issues that are clearly shown by the displays. There appears to be a larger than normal gap between the two

Figure 24 Temperature variations with furnace operating on a fairly regular schedule.

Figure 25 Examples of the temperature data when furnace operation is less regular and gas inlet temperature exceeds 1200°C.

Figure 26 Infrared camera in position for viewing recuperator tubes.

(#3 and #4) modules on the right. Also, the two tubes on the left side of module #3 appear to be bent considerably out of their normal positions. Also, the color in the last display shows that the hottest areas are slightly off center - the last tube in module #2 and the first three tubes in module #3. Furthermore, the hottest areas are well above center. Although it is not apparent in the four displays in this figure, there was some evidence that the refractory lining at the top of some of the modules had fallen. This displaced refractory suggests the recuperator tubes were deformed badly enough to cause the refractory to crack and fall, and the upper “tubesheet” was exposed to very high temperatures since the protective refractory was gone. Even though the IR camera is looking at the tubes in a line not perpendicular to the rows of tubes, there is only one location (second tube in module #3) where a tube from the second row is hot enough to be detected by the camera. This is an indication that the tubes in the first row get a lot hotter than tubes in any of the other rows.

One day’s worth of IR camera work was conducted as part of the demonstration, and Logan Aluminum subsequently chose to rent the camera for longer periods on at least one occasion. On the day of the camera demonstration, a representative of the recuperator manufacturer was there to observe the demonstration. Later in the afternoon, discussions were held to evaluate the results of the demonstration. The manufacturer’s representative noted that the recuperator design had evolved and was not the result of any detailed modeling of gas flow. In fact, he indicated he was not aware of any modeling work ever being done on the recuperators.

The lack of uniformity in measured temperatures across the first row of recuperator tubes as well as the apparent significantly lower temperatures of the other rows of tubes suggests there is a lot not understood about flow of combustion air in the tubes and the flue gas around the outside of the tubes. This led to a decision to employ computational fluid dynamics (CFD) and finite element (FE) modeling to try to understand the flow of gases through and around the tubes. Since the recuperator manufacturer had not performed any modeling of the recuperator, it was concluded this could provide some real value.

(a)

(b)

(c)

(d)

Figure 27 Sequence of infrared camera pictures showing recuperator modules. The color change from blue to red to yellow indicates increasing temperature. Note the hottest spot is slightly to the right and up from center where the bent tubes can be seen.

COMPUTATIONAL FLUID DYNAMICS AND FINITE ELEMENT MODELING OF RECUPERATORS

This section describes the modeling work that has been carried out to understand the effect of the design and operating conditions of the recuperator on the tube temperature distribution, and how this in turn might influence the distortion of the tubes. Modeling to examine the flow of air through the recuperator tubes was carried out using the commercial computational fluid dynamics code FLUENT. The effect of the temperature variation around the tube circumference on the resulting distortion was studied using the commercial finite element structural analyses code ABAQUS.

Each recuperator bundle consists of an inlet and an outlet header for the air at the top, with each header connected to a rectangular array of tubes. There is also a plenum at the bottom through which the air flows from the inlet towards the outlet side. Figure 28 shows a schematic view of the recuperator, with a 12×3 arrangement of tubes on each side. The actual recuperator at the aluminum mill uses a 20×5 arrangement of tubes (as shown in Fig. 7), but initial modeling work to study the flow of air through the recuperator was carried out using the simpler 12×3 arrangement. Figure 29 shows the mesh for the top section of the recuperator generated using tetrahedral elements. The simulations were carried out by prescribing the velocity of air at the top cross-section of the inlet header.

The path lines for the flow through the recuperator for an inlet velocity of 10 m/s are shown in Fig. 30. The colors correspond to the simulated flow of individual particles through the tubes which are used to generate the path lines. It can be seen that after passing through the tubes on the inlet side (right side), most of the air flow is across the bottom plenum towards the tubes near the end, with much less flow through the tubes near the center on the outlet side (left side). The non-uniform nature of the flow through the different tubes can also be seen from the contours of the velocity in the z-direction in a cross-section perpendicular to the tube length taken about

Figure 28 Schematic view of the recuperator with a 12×3 arrangement of tubes.

Figure 29 Mesh for the top section of the recuperator with a 12×3 arrangement of tubes generated using tetrahedral elements.

halfway along the tube length. These are shown in Fig. 31, and it is seen that on the inlet side, the velocity is highest for the tubes near the middle, while on the outlet side, the velocity is higher for the tubes on the end, and lower for the tubes near the center of the recuperator. This difference in the velocity between the different tubes became even more apparent when the simulations were carried out using hexahedral elements, as shown in Fig. 32 for the entire cross-section, and in Fig. 33 for a closer view of only the outlet side. Simulations were also repeated with inlet velocities of 5 m/s and 15 m/s, and it was found that the flow became more non-uniform with increasing velocity.

Path Lines Colored by Particle ID

May 23, 2006
FLUENT 6.1 (3d, segregated, ske)

Figure 30 Path lines showing the flow through the recuperator with a 12×3 arrangement of tubes for an inlet velocity of 10 m/s. Colored lines represent flow in the tubes.

One of the simplifications made during the initial model development was to neglect the presence of any discontinuities in the base of the bottom plenum. An inspection of several recuperators removed from service for repairs revealed the presence of several potential sources for disruption of the flow in the bottom plenum. These include spiral strips placed in the tubes to cause greater flow mixing (some of which had fallen into the bottom plenum), fork lift slots for ease in moving the recuperator modules as well as reinforcement strips at various locations along the inner walls of the bottom plenum (see Figs. 34 and 35). The model for the recuperator was

Figure 31 Contours of velocity along the z-direction for the recuperator with a 12×3 arrangement of tubes discretized using tetrahedral elements for an inlet velocity of 10 m/s.

Figure 32 Contours of velocity along the z-direction for the recuperator with a 12×3 arrangement of tubes discretized using hexahedral elements for an inlet velocity of 10 m/s.

modified to include the forklift slots, as shown in the schematic view in Fig. 34. The path lines for the flow using this geometry for an inlet velocity of 10 m/s are shown in Fig. 36, and it is evident that the forklift slots cause a disruption of the flow in the bottom plenum, thereby reducing the flow through the tubes towards the outside and increasing flow through the tubes.

Figure 33 Contours of velocity along the z -direction on the outlet side of the recuperator with a 12×3 arrangement of tubes discretized using hexahedral elements for an inlet velocity of 10 m/s.

Figure 34 Schematic view of the recuperator with a 12×3 arrangement of tubes including the forklift slots in the bottom plenum.

Figure 35 View looking into the lower plenum of recuperator module showing the spiral strips which have come loose and dropped into the plenum as well as the raised areas that provide slots used by the forklift to raise and move the module.

Path Lines Colored by Particle ID

Sep 07, 2006
FLUENT 6.1 (3d, segregated, ske)

Figure 36 Path lines showing flow through the recuperator with a 12×3 tube arrangement with forklift slots in the bottom plenum for an inlet velocity of 10 m/s. The density of the colored lines is proportional to the quantity of air flowing in the tubes.

close to the center on the outlet side. While other sources of flow disruption were not modeled due to the complexity involved, it is evident that they would also have a similar effect on the flow through the tubes, potentially further decreasing the flow rate of air through the tubes on the outside. This in turn would limit the effective cooling of these tubes, since they have the most direct and maximum exposure to the flue gas coming from the furnace.

The model for the recuperator was further extended to include the flue gas coming from the furnace exhaust that flows across the tubes, as shown schematically in Fig. 37. Both heat transfer and gas flow were considered in the analysis. The inlet flow rate for air was taken to be $10^6 \text{ ft}^3/\text{hr}$, which corresponds to an inlet velocity of 48 m/s. The air temperature at inlet was assumed to be 25°C (298 K). The flue gas temperature at the inlet was assumed to be 1050°C (1323 K), with a flow rate of $1.3 \times 10^6 \text{ ft}^3/\text{hr}$, which translates to an inlet velocity of 1.2 m/s. The tube material was assumed to be steel with a wall thickness of 0.25 in. (6.35 mm). Figure 38 shows the pathlines for the flue gas flow (which is from left to right) across the recuperator tubes, and it is evident that beyond the first row of tubes, the contact with the flue gas is limited to the sides of the tubes. The results from the analysis showed the temperature of the air at the recuperator outlet header to be much lower than typical measured values, and this was thought to be a consequence of the simplified 12×3 arrangement of tubes. As mentioned earlier, the actual recuperator used in the aluminum mill has a 10×5 arrangement of tubes on both the inlet and outlet sides, which would result in a larger surface area for heat transfer.

Figure 39 shows the schematic for the recuperator with the 20×5 arrangement of tubes including the volume for the flue gas. The simulation was initially carried out using the same assumptions for the air and flue gas temperatures and flow rates as described above. In the actual set up, there are four sets of recuperator bundles each with a 20×5 arrangement of tubes that are placed next to each other. Assuming the air flow rate of $2.8 \times 10^4 \text{ m}^3/\text{hr}$ ($10^6 \text{ ft}^3/\text{hr}$) to be the combined value,

Figure 37 Schematic view of the recuperator with a 12×3 arrangement of tubes including the forklift slots in the bottom plenum and the flue gas flow across the tubes.

Figure 38 Path lines showing flow of flue gas across the recuperator tubes. The density of the colored lines is proportional to the quantity of air flowing between the tubes.

another simulation was carried out with the air inlet velocity of 12 m/s. The furnace operation goes through a series of melting cycles, so that at the end of each cycle, the flow rate of both the air and the flue gas is roughly half of the peak value. In order to analyze this situation, another simulation was carried out assuming the air flow rate to be 6 m/s and the flue gas flow rate to be 0.6 m/s.

Figure 39 Schematic view of the recuperator with a 20x5 arrangement of tubes, including the forklift slots in the bottom plenum and the flue gas flow across the tubes.

For this particular furnace, in an effort to provide additional cooling, one of the recuperator bundles has the air flow reversed relative to the other three (with the inlet header facing the flue gas, so that air flow in the bottom plenum is parallel to the flue gas flow), and the maximum air flow rate through each recuperator is about of $8.5 \times 10^3 \text{ m}^3/\text{hr}$ ($300,000 \text{ ft}^3/\text{hr}$) for normal flow and of $6.2 \times 10^3 \text{ m}^3/\text{hr}$ ($220,000 \text{ ft}^3/\text{hr}$) for reversed flow. This corresponds to a velocity of 14.4 m/s for the normal (counter) flow arrangement, and a velocity of 10.5 m/s for the reverse (parallel) flow arrangement. Simulations using these values were also carried out, and for these simulations, the material properties were also modified to consider temperature dependent properties for air and HE steel (for the tube material). Table 2 shows a summary of the results for the various cases considered, along with the assumptions for the inlet flow rates. The last two columns show the results for the maximum air outlet temperature and the minimum flue gas outlet temperature for the different cases. In the first column, below each case number is shown the assumption regarding the tube material (generic steel or HE steel with temperature dependent properties), and whether temperature dependent properties for air were used.

Comparing cases 1-3, it is seen that reducing the air flow rate through the recuperator leads to an increase in the air outlet temperature, due to the longer residence time for the air in the recuperator tubes, and hence greater heat transfer. The effect on the flue gas temperature at the outlet is much more modest. Use of temperature dependent properties for HE steel for the tube material (case 4) did not lead to much difference from use of properties for a generic steel (case 3). However, use of temperature dependent properties for air (case 5) led to a lower maximum air outlet temperature and a slightly lower minimum flue gas outlet temperature, compared to the use of constant property values for air (case 2). Reversing the flow (case 6) also led to slight increases in the temperature of both the air and flue gas at the respective outlets.

Table 2. Summary of gas velocities and temperatures for the recuperator with 20×5 arrangement of tubes for different cases analyzed.

	Air inlet velocity [m/s]	Flue gas inlet velocity [m/s]	Maximum air outlet temperature [°C]	Minimum flue gas outlet temperature [°C]
Case 1 (Steel)	48	1.2	160.7	776
Case 2 (Steel)	12	1.2	284.5	786
Case 3 (Steel)	6	0.6	317	773.8
Case 4 (HE Steel)	6	0.6	316	773.9
Case 5 (HE Steel + air)	14.4	1.2	171	753
Case 6 (rev.) (HE steel + air)	10.5	1.2	184.5	760

Figure 40 Temperature contours of the flue gas in contact with the tube surface for case 5 (normal flow with temperature dependent properties for HE steel and air).

In addition to the temperature of the air and flue gas at the outlet, another aspect that was examined was the temperature of the flue gas in contact with the tube surface, which represents the temperature at the tube surface. Figure 40 shows the temperature contours for case 5 with normal flow arrangement, and it is evident that tubes in the first row have the highest temperature (maximum value of about 504°C). Figure 41 shows similar temperature contours for case 6 with reverse flow arrangement, and the temperature of the first row of tubes is somewhat lower, suggesting some benefit in operating with this arrangement.

One of the goals of the modeling effort was to determine the effect of the recuperator design on the flow and temperature distribution, and to this end, it was determined to make some modifications to the current design. The first change involved removing the first row of tubes (that face the flue gas) and plugging the last two rows of tubes on the outlet side of the recuperator, as shown schematically in Fig. 42. In addition to this, another modification was to introduce a false floor in the bottom plenum at the top of the forklift slots, in effect reducing its height by 4 in. (10.2 cm). For each of these modifications in design, two cases were simulated, one corresponding to maximum flow conditions, and the other corresponding to reduced flow conditions, and the results for this study are summarized in Table 3.

As seen from the results in Table 3, for the maximum flow condition, removing the first row of tubes and plugging the last two rows of tubes on the outlet side leads to a temperature reduction at the tube surface of about 65-70 C°. This is also evident from the contour plots of the temperature at the tube surface shown in Figs. 43 and 44, for the current design and the reduced number of rows, respectively. There is also a reduction in the maximum air outlet temperature, and a slight increase in the minimum flue gas outlet temperature for this case. Introduction of a false floor at the top of the forklift slots does not lead to much change in these results. For the cases with the lower flow rate (corresponding to the end of the melting cycle), once again the change in design leads to a reduction in the maximum temperature at the tube surface, as seen

also in the contour plots of the tube temperatures shown in Figs. 45 and 46. The results with the false floor are not very different from those with the forklift slots, suggesting that in this case, the major effect comes from the reduction in the number of rows on the outlet side.

In addition to the analysis of the flow and temperature distribution in the recuperator bundle described above, finite element modeling was also used to study the distortion of a single tube

Figure 41 Temperature contours of the flue gas in contact with the tube surface for case 6 (reversed flow with temperature dependent properties for HE steel and air).

Figure 42 Schematic view of the recuperator with a 20×5 arrangement of tubes, with the first row of tubes facing the flue gas removed, and last two rows on the outlet side plugged.

due to the variation in temperature around the circumference of the tube. Most of the recuperators taken out for repairs have shown severe distortion of the first row of tubes exposed to the flue gas, suggesting that one side of the tube experienced a much higher temperature than the opposite side. The path lines for flue gas flow across the tubes (Fig. 38) show that the first row of tubes is in contact with the flue gas on the front side only, with very little or no contact on the back side.

The simulations were carried out using the commercial code ABAQUS using a geometry consisting of two tubes, the first representing recuperator tubes from the first row (facing the flue gas), and the second representing tubes in the remaining rows that are at a lower temperature. The tubes, initially at room temperature, were heated to operating conditions and then cooled back to room temperature. Temperature values on the outer surface of these tubes were specified at operating conditions, such that the first tube had a variation in temperature from the front to the back side, and also had a higher temperature in the mid-section compared to the top and bottom sections (along the tube length) on the front side, as shown in Fig. 47. The second tube was assumed to have a uniform temperature distribution, with a value that is lower than the temperature of the first tube.

Since the tubes are supposed to be connected through the headers and the bottom plenum of the recuperator, the second tube acts to constrain the free axial expansion and contraction of the first tube during heating and cooling. This constraint was enforced using two methods, the first based

Table 3. Summary of gas velocities and temperatures for the recuperator with a 20×5 arrangement of tubes, showing the effect of removing the first row and plugging the last two rows of tubes on the outlet side.

	Air inlet velocity [m/s]	Flue gas inlet velocity [m/s]	Maximum air outlet temperature [°C]	Minimum flue gas outlet temperature [°C]	Maximum flue gas temperature at the tube surface [°C]
Case 1a (current design)	14.4	1.2	259	796.5	607
Case 2a (reduced rows)	14.4	1.2	226	817.9	539
Case 3a (reduced rows with false floor)	14.4	1.2	225.8	817.9	538
Case 1b (current design)	6	0.6	317	773.8	669
Case 2b (reduced rows)	6	0.6	276.9	794.5	596
Case 3b (reduced rows with false floor)	6	0.6	285.8	795.6	601

on a linear constraint equation that makes the axial displacement of the two tubes the same, and the second based on setting the axial displacement of the first tube to be the same as the free expansion of the second tube. Figure 48 shows the distortion of the tube based on the first constraint method, and a similar result was also obtained from the second method.

Figure 43 Temperature contours of the flue gas in contact with the tube surface for the current design under maximum flow conditions (case 1a).

Figure 44 Temperature contours of the flue gas in contact with the tube surface with reduced row of tubes on the outlet side under maximum flow conditions (case 1b).

Figure 45 Temperature contours of the flue gas in contact with the tube surface for the current design under reduced flow conditions (case 2a).

Figure 46 Temperature contours of the flue gas in contact with the tube surface with reduced row of tubes on the outlet side under reduced flow conditions (case 2b).

Figure 47 Temperature contours for the two tubes at operating conditions.

Figure 48 Distortion in tube 1 due to the non-uniform temperature distribution based on method 1 for the constraint from the cooler tube 2.

While the temperature values used to obtain distortions of sufficient magnitude seen in actual tubes are as high as 1300°C, temperature measurements based on thermocouple data and the infrared camera would suggest that it is conceivable for some of the tubes to reach temperature values of that magnitude.

One thing not addressed in the CFD modeling is the effect of the spiral pieces, inserted in each of the recuperator tubes, that have come loose and dropped into the lower plenum of the module (Fig. 35). These pieces, which are nearly the width of the tube ID, potentially cause a good deal of turbulence in the plenum and reduce the amount of air that flows to the end of the plenum and through the first row of recuperator tubes.

Table 4. Summary of tube temperatures and displacements from analyses of tube distortion for different assumptions for the tube temperatures.

Tube 2 [°C]	Tube 1 front max [°C]	Tube 1 front top [°C]	Tube 1 front bottom [°C]	Tube 1 back [°C]	Maximum distortion (Method 1) [mm]	Maximum distortion (Method 2) [mm]
650	1100	1000	950	650	29.1	34.8
650	1200	1000	950	650	44.4	44.2
650	1200	1000	950	850	32.3	16.3
500	1200	1000	950	850	20.7	22.2
650	1300	1000	950	650	54.6	44.8
500	1300	1000	950	500	78.8	71.9

DISCUSSION

As a result of many discussions with the aluminum company's personnel, several relevant things were learned. During the melting operation, no fluxes (chlorides or fluorides) are intentionally added to the melt. It is possible that some of the material in the furnace charge contains low levels of chlorides and/or fluorides, and this could account for the low levels of chlorates seen in some of the scale analyses. However, the severe thinning of the recuperator tubes is probably not significantly accelerated by the presence of a fluxing agent.

The CFD modeling shows there are many things that could and should be changed to improve the distribution of combustion air in the recuperator tubes and the flow of flue gases around the tubes. With the current recuperator design, the first row of tubes will likely have a lower flow of combustion air than tubes a few rows away from the front of the module (closer to the center of the module). Reducing the sources of disruption to the flow in the bottom plenum would be beneficial for increasing the flow rate of air through the first row. In this respect, improvements to the welding of the spiral strips are needed to prevent them from detaching and falling into the bottom plenum. Furthermore, the current design does relatively little to promote heat transfer from the flue gas to the tubes behind the first row. Alternate tube arrangements, such as a triangular array instead of the currently used rectangular array of tubes, need to be considered.

The melting furnaces at the particular facility where the recuperator studies were conducted all have their characteristic features. All have ports for addition of dilution air, but only furnace #3 has four recuperator modules; the others have three modules. The furnace in which no testing was done (#1) has an unused bypass that offers a possible means of addressing the increased heating of the recuperator tubes when the flow of combustion air is reduced. This bypass is positioned so that preheated air does not have to go to the burners but could be diverted to another location or application. This would permit the operators to maintain a high rate of air flow through the recuperator tubes whether or not the burners were in use.

The finite element modeling shows that non-uniform heating of the recuperator tubes is the likely cause of the tube deformation. There are several ways to address this including better cooling of the tubes, relaxing of the constraints on the ends of the tubes and using a tube alloy with a lower coefficient of thermal expansion.

CONCLUSIONS

For the recuperator tubes studied, high temperature oxidation and oxide spalling during thermal cycling were the major causes of tube degradation.

Temperature measurements with thermocouples and an infrared camera characterized the variation in tube temperatures. Temperatures in selected areas were shown to routinely exceed 1000°C and to reach at least 1100°C on some occasions.

Computational fluid dynamics modeling showed the non-uniformities in air flow through the recuperator tubes. In particular, flow of the combustion air through the bottom plenum of the recuperator module was strongly affected by components that protruded into the plenum, and these generally reduced the amount of air reaching the first row of recuperator tubes.

Finite element modeling provided an explanation for the warping and bending of tubes in the first row of the recuperators.

Information collected from suppliers of heat recovery systems for the aluminum industry showed recuperators are being used less in the U.S. in part because of the high maintenance costs.

Recommendations of alternate tube materials and recuperator design changes were offered.

RECOMMENDATIONS

One of the original objectives of this task was to identify alternate alloys that would give improved life as recuperator tubes. From the information collected regarding the temperatures reached by some portions of the tubes, it appears that changing the tube alloy might give slight improvement in performance, but operational changes would potentially have more impact. If other alloys were to be considered, an alumina-forming alloy, such as Kanthal APM or APMT, Special Metals MA956 or Haynes International Alloy 214, should be given serious consideration. Because of their ability to form an alumina surface layer, these alloys are more resistant to oxidation at elevated temperature than the chromia-forming alloys.

The bypass ducting that is in place (but unused) on one of the furnaces should be brought into operating condition and then tried during periods when the furnace is hot and the need for pre-heated combustion air is lowest. It would be particularly informative if the IR camera could be used on this furnace during cycles with and without implementation of the bypass ducting.

Significant redesign of the recuperator modules should be considered. This would include putting the tubes on a staggered arrangement, reducing the number of tubes, installing internal guides to direct more of the combustion air through the first row of tubes, making the upper tubesheet more flexible and using a refractory that will be less likely to crack and fall out. In any case, use of CFD modeling to evaluate the effect of any changes should be considered.

The IR camera proved to be a very useful tool for determining the temperature of the recuperator tubes and should be equally useful in determining the temperature in other areas of the entire furnace system. Purchasing or periodically renting an IR camera and then regularly monitoring the conditions of the recuperator tubes would provide a means to assure the recuperators were operating under the desired conditions.

APPENDIX

Notes from contacts with Recuperator Suppliers – Compiled by Arvind Thekdi

Alstom Power Inc. (formerly American Schack Company, Inc.)

Alstom Power Inc., Energy Recovery, located near Pittsburgh in Wexford, PA USA (formerly American Schack Company, Inc.) is a supplier of specialty design heat transfer and heat recovery equipment. Their heat recovery equipment operates in some of the most aggressive and difficult environments in industry, including steel (and other primary metals), refinery, petrochemical, glass, waste incineration, and carbon black. Their heat recovery equipment consists of heat exchangers, recuperators, waste heat recovery boilers, specialty fired heaters, and specialty waste gas incineration equipment. The equipment design requires operations in hard-to-handle applications - dirty gases, high temperatures, corrosive / erosive environments, and any other application, which requires a specialized, non-standard equipment design.

Specifically the division in USA and their associates in Duesseldorf, Germany (Alstom Power Energy Recovery GmbH, formerly Rekuperator K-G) have been active in aluminum and glass industries for recuperation of heat from high temperature contaminated gases.

The following section gives their response to specific questions we asked them.

1. What are commonly used designs and what are the positive and negative features of each?

For most glass and aluminum recuperator applications, a double shell radiation recuperator is a suitable option for heat recovery. It can be operated with flue gas entering at 2200°F, 2400°F or higher if needed, it can be used to preheat air to approximately 1100 to 1200°F, it has good molten slag characteristics for operation in glass furnaces, it has very low flue gas pressure drop, and it has reasonable costs. It is limited by air temperature (usually anything over 1200°F needs another design) and air pressure (normally no more than approximately 1 to 2 psig). For higher air preheat & pressure, a radiant tube cage recuperator is useful, although it is somewhat more expensive. We have also done 2 stage recuperators, with part of the heat recovery in a cage, and part in a double shell. In glass and aluminum, at lower temperatures (below approximately 1200°F), a more typical convective heat exchanger (canal or channel type) can be used, with soot blowing for on-line cleaning.

2. What alloys are used or offered for the recuperator tubes (or metallic plates)?

They have used a great number of alloys for various equipment designs, depending on the application, customer preference, etc. In aluminum, we typically only see high temperature oxidation-resistant materials (T304, maybe some T309 or T310), since the dust is normally "dry" and not a strong corrosion concern. There can still be fouling due to the dust buildup, but this can be accounted for with increased surface area. For glass, however, normally a corrosion resistant material is required, since the molten glass will collect on the exposed surface. Many times this is T309, but many times it is high nickel such as 800/800H, etc. Furthermore, fouling can be increased in a glass furnace recuperator due to the consistent layer of molten glass on the inside. Typically they try to maintain a high metal temperature for glass applications to promote

molten conditions (molten material can flow down and drip back into the furnace) rather than allowing it to "solidify" on the surface.

3. Have you done any CFD modeling of the air flow in the recuperator tubes and/or the flue gas flow across the tubes? If yes, would you like to share the results with the Oak Ridge National Laboratory on a confidential basis for review and possible help? If not, would you be interested in working with the ORNL if they were to do this modeling?

Schack Company does not have CFD modeling capabilities in-house, and as far as I know have never had CFD modeling performed on one of their designs. Typically they have found the cost of such modeling to be prohibitive, and the output of such modeling will be questionable at best. However, if ORNL were interested in performing CFD modeling on equipment designed by APER, they would be happy to provide, within reason, any necessary layout, & geometry information needed to perform such a model.

4. How many recuperators are you selling to different industries? Are you supplying the replacement tubes to the recuperator user? In any case how many replacement tubes are sold annually?

The following is a list of some of the "typical" applications we work with.

- Air preheaters for the carbon black industry (preheating reactor combustion air, using particulate-laden reducing gas exhaust from the reactor).
- Air preheaters / recuperators for the municipal sludge incineration market (preheating fluidizing air for the fluid bed, using particulate-laden furnace exhaust gas).
- Heat exchangers for thermal oxidizers (preheating fume / combustion air, using exhaust gas from the thermal oxidizer).
- Heat exchangers for direct reduced iron plants (preheating reformer combustion air and process gases, using reformer exhaust gases).

On occasion the company will provide spare parts for these units, including spare tubes. However, performing renovation work in the field can be challenging. Therefore, more often they will provide re-build services - taking the existing heat exchangers from the field to a manufacturing shop, and repairing / replacing portions to return it to newer operating conditions. Also, they often supply spare heat exchanger modules to replace entire sections of the equipment. Spare parts / spare & replacement equipment account for small percentage of their annual sales in a typical year.

5. Can you identify companies that are using recuperators so that ORNL can ask them to participate in our project?

A reference list can be provided to identify some of the key customers for applications in the glass and aluminum industries.

6. Would you (the suppliers) be interested in working with us on the project?

They would certainly be interested in working with us to develop potential heat recovery applications in the glass and aluminum markets. Obviously they have other time & resource

constraints, but whenever possible they will make them available to provide information, ideas / concepts, and data on heat recovery equipment.

Bloom Engineering

Bloom Engineering Inc. is a burner and furnace insulation parts supplier company headquartered in Pittsburgh, Pennsylvania. It serves many industries with a very strong position in steel and aluminum industries. Over forty years ago, Bloom developed the unique baffle burner concept which is applied to its direct fired burners and regenerative burners. The concept is particularly useful in reducing NO_x and hence their regenerative burners claim to have the lowest NO_x emissions even with use of highly preheated air.

Bloom Engineering was contacted to discuss flue gas heat recovery systems from aluminum melting furnaces. They have extensive experience in steel and aluminum industry and he has worked for many projects in which high temperature flue gases are used to preheat combustion air to as high as 1400°F temperature in reheat furnaces operated at 2200 to 2300°F. They are currently working on a number of projects for USA and International installations.

Initially they provided background on rapid growth of regenerative system applications and mentioned that a typical aluminum melting furnace discharges flue gases in temperature range of 1800 to 2200°F. A high efficiency recuperator can offer a heat recovery efficiency of 50% to 55% and deliver preheated air at about 1000°F. A regenerative burner system has an efficiency of 72% to 75% and delivers combustion air at about 1400 to 1500°F. The effect of this is to reduce fuel consumption by 30% for recuperators and by 40% for regenerators. This difference is significant when one considers effect of this on possible increase in production or melt rate. Most companies drive their furnaces hard to get 5% to 10% higher production and that results in higher flue gas temperature and severe damage to a recuperator. Push for higher production has resulted in higher input, higher flue gas temperatures (sometime far above the material design limitations) and often inefficient combustion that increases fuel consumption by a significant amount (10% to 20%), wiping out the expected benefit of use of recuperator. The companies often neglect maintenance on recuperators and the end result is even more fuel consumption in furnaces.

However higher inputs and push for production does not have as bad an effect on regenerative systems as it is for recuperative systems since the regen systems use non –metallic parts with very high temperature capabilities.

The regen burners do present problems related to plugging of the bed when the furnaces are operated with dirty scrap, generate high percentage dross and generate soot particles. The problem is more severe during fluxing however an automatic control of the system allows by passing of the regenerative system when the user performs batch fluxing. Continuous fluxing, rarely used, could present a problem if the fluxes are highly corrosive to the ceramic materials.

It is necessary to clean the bed to avoid degradation of performance and reduction in firing rate that in turn would result in drop in melt rate and production. It is necessary to change the bed when it “plugs up”. A bed would remain clean for several months if the furnace operation is with clean charge material. However most users would charge some type of purchased scrap that may contain impurities. In this case it is necessary to change the bed periodically – ranging from once a week to once a month. Changeover of bed required approximately ½ hour during which time the furnace continues to run using bypass dampers and cold air. The end effect is loss of

efficiency during this time. The bed needs to be cooled and cleaned by water spray which may take one shift or longer. In most companies a spare bed is maintained to replace a plugged bed while one of the beds is being cleaned and kept ready for the next changeover. There is very little, if any, attrition from the ceramic balls that are made out of alumina.

The bed container is stainless steel box that is lined with insulation inside. The balls are supported on a carbon steel or stainless steel supports. The entire assembly can withstand very high enrapures without any effect on the performance or safety concerns for the system.

Bloom supplies the entire system that includes regenerative bed, burners, associated valves and linkages and furnace temperature controls. The system uses a fairly complex (compared to simple burner-recuperator system) control system to maintain the heat recovery and continuing efficient operation. It is necessary to use PLC controls and employ a technician or engineer with knowledge of PLC controls. The burner suppliers can provide periodic service on contract basis to maintain the system,

Bloom claims to have a heavier, sturdier burner with “simple” controls. The burners are ceramic lined to with stand temperature excursions if any. Their baffle design allows them to maintain extremely low values for NO_x emissions. They have two different versions of low NO_x burners. The ultra low NO_x burner offers 0.1 Lb per MM Btu while the normal low NO_x burner offers 0.13 lb. NO_x per MM Btu.

The cost of this system compared to cold air burner is almost 3 times and 1.5 times the cost of recuperative system. However the life cycle cost analysis and payback period analysis at today’s energy prices (\$7 to \$10 per MM Btu) can easily justify the higher initial cost. The simple payback period is usually less than one year and it is significantly lower if one considers value of increased production related economics.

They do not see any major R&D requirements for the materials. They would like to see some work done on controls and associated hardware such as valves. These valves open and close every 20 seconds and require duty of millions of cycles per year. They have not seen any premature failure of these valves however it is a maintenance item that has to be addressed if you have many furnaces using this system.

Bloom would be happy to supply their customer list.

Conclusion and Comments:

Regenerative burners seem to be replacing conventional recuperator type waste heat recovery design. They offer an excellent opportunity to increase energy efficiency and furnace productivity simultaneously with acceptable pay back periods. Bloom being one of the two major (and perhaps the only two) suppliers in US has a very strong market position and considerable experience in design and operation of these systems.

It will be useful to contact several users of regenerative burners, particularly those who have switched from recuperative systems to regenerative systems, to get their side of the story and requirements. The burner suppliers do not see materials R&D needs; however they can reduce the size of the unit significantly if we were to consider development of high heat capacity material or composite that can retain higher heat per unit volume. Right now the main objection to the use of regenerative burners in existing installation is its size. Often time the two or four burners require as much room as the furnace foot print itself. The recuperators are large but they

sit on the top of a furnace however the regenerators have to be located on the side of the furnace and require additional “foot print” space.

DesChamps Technologies

DesChamps Technologies is a major supplier of specialty design heat transfer and heat recovery equipment. Their heat recovery equipment includes high and low temperature recuperators, gas coolers, gas heaters etc. used for heating and cooling of fluids using waste heat from flue gases. Many of this equipment can be operated using gases with little or no contaminations. However the design offers much higher heat transfer rates and is very compact. They have supplied heat exchangers, combustion air preheaters and other heat recovery systems for various industries including aluminum industry. They offer standard and custom made equipment.

The following section gives their response to specific questions we asked them.

1. What are commonly used designs and what are the positive and negative features of each?

DesChamps offers several different designs and configuration of heat exchangers. The designs include cross flow, co-current flow and counter current flow configurations. Their design primarily uses convection mode of heat transfer and they do not supply radiation type design. They have supplied units for a wide range of temperature applications ranging from 400°F to as high as 2000°F. Beyond 2000°F they use ceramic matrix design and can go to much higher temperatures. The designs are best used for relatively clean gases from thermal oxidizers, steel heat treating furnaces or aluminum holding furnaces where the gases contain very little particulates or corrosive materials. The designs are very compact and offer much higher heat transfer for a given volume or foot print of the heat exchanger. main advantage is use of relatively smaller space and flexibility in configurations to meet the specific site requirements. The units can last for 5 to 10 years in cleaner gas applications and 3 to 5 years in “dirty” gas environment. They can design units for contaminated gases using wider space between the heat transfer surfaces and allow for cleaning by “washing” or “flushing” the surfaces to clean them. Almost all of their units are fabricated using wrought alloy materials.

2. What alloys are used or offered for the recuperator tubes (or metallic plates)?

DesChamps uses a large variety of alloys for different designs. For relatively lower temperatures (below 1400°F flue gases) they use all types of stainless steels *304, 316, 309, 310 etc.). They also use 600 series alloys such as 600, 610, 625 etc. They do not use cast alloys since almost all of their units are fabricated from sheet materials. For higher temperatures and critical designs they use high temperatures alloys with high strength (310 or 605 or alternates). 310 is their preferred material. For higher temperature they go to SiC or Si - Nitride materials and they are cast plate or core type design.

3. Have you done any CFD modeling of the air flow in the recuperator tubes and/or the flue gas flow across the tubes? If yes, would you like to share the results with the Oak Ridge National Laboratory (ORNL) on a confidential basis for review and possible help? If not, would you be interested in working with the ORNL if they were to do this modeling?

DesChamps does not have CFD modeling capabilities. All of their designs are based on "proven" calculations by Dr. Nick DesChamps, carried out over the last 30 years and have been

tested in their R&D labs plus the field data. They have developed and tested several models of their standard designs and feel very comfortable with the performance prediction capabilities. Since the applications are considered carefully to match their own extensive experience base and their use of “conservative” designs they have not felt that it is necessary to devote resources for CFD analysis.

They may be interested in performing CFD analysis but the cost for software, training and trial-error steps seem to be cost prohibitive. They may discuss working with ORNL to pursue CFD analysis activities however many of their designs are proprietary and would be very concerned about issues related to confidentiality, sharing of proprietary drawings etc. Such discussions would require discussions with their President Dr. Nick DesChamps.

4. How many recuperators are you selling to different industries? Are you supplying the replacement tubes to the recuperator user? In any case how many replacement tubes are sold annually?

The number of recuperators sold varies considerably from year to year and from industry to industry. DesChamps has supplied hundreds of compact recuperators to various industries. Their industrial units described in their brochures are mostly supplied for heat recovery in thermal oxidizers, heat treat furnaces, the methanol industry, automobile industry ovens and furnaces, ovens etc. Their experience with aluminum industry furnaces heat recovery is limited to holding furnace where the gases are relatively clean or the designs can be cleaned periodically. They do not see much activity in the aluminum industry.

Their “tube” or “matrix” replacement business is minimal because they supply the unit that can be cleaned and can be maintained for relatively long time (5 to 10 years) when the user may replace the entire unit. This business is a very small percentage of the total business.

5. Can you identify companies that are using recuperators so that ORNL can ask them to participate in our project?

DesChamps has a long list of references for many different industries however their list of aluminum applications is limited to “clean” gas applications. They can supply the customer list if required.

6. Would you (the suppliers) be interested in working with us on the project?

DesChamps has worked with various sections of DOE – EERE, particularly the areas where they have developed designs for heat recovery for the Distributed Generation Office. They would be interested in working with ORNL with appropriate confidentiality and proprietary information protection to develop potential heat recovery applications in the aluminum industry or any other industry. They would like to consider what they could gain vs. the time and other resources spent on the collaborative efforts. They are willing to pursue this further.

Conclusion:

DesChamps is one of the very few US owned and operated companies that supplies a wide variety of heat exchanger equipment. They also have a history of working with DOE ever since its inception. They are not very active in aluminum melting furnace heat recovery primarily due to their heat transfer surface design and configuration that requires small passages but compact configuration. However their approach of periodic cleaning of the heat transfer surfaces has

been very effective in other applications where a large amount of contaminants are present in hot gases. They do not seem to be a good candidate for applications where the gases contain condensable material that may adhere to the heat transfer surfaces and it is difficult to remove the material adhered to the heat transfer surfaces.

North American Manufacturing Company

North American Manufacturing Company is an almost 90 years old company that supplies various components of a heating system including regenerative burners used in aluminum melting furnaces. They are located in Cleveland, OH. North American is one of the two companies supplying regenerative burners to the US market.

The North American Mfg. Co. product manager for the aluminum industry equipment informed us that their burners were originally designed by Tokyo Gas Co of Japan and at this time North American has exclusive worldwide license to produce these burners. The primary goal for the Japanese design was to maximize heat recovery while minimizing the NO_x emissions to meet Japanese standards.

They basically reaffirmed information provided by Bloom Engineering. The designs are very similar to the point that there have been some legal issues between the two companies. Use of regenerative burners is increasing very rapidly in the US as well as internationally due to high energy prices and also success stories published in various trade journals and presentations in conferences. Their performance can offer energy savings varying from 30% for 1460°F flue gases to as high as 69% for very high temperature furnaces with 2640°F exhaust gas temperature. For the aluminum industry they can achieve 35% to 40% fuel savings. This represents heat recovery efficiency in excess of 75%.

North American burner design uses two different techniques to stabilize the flame while reducing NO_x. They supply the design to meet customer requirements of NO_x emissions.

Justification for use of regenerative burners over the recuperators was very much like the justification given by Bloom Engineering. The following may look like repetition of what is mentioned in Bloom Engineering contact notes.

A typical aluminum melting furnace discharges flue gases in the temperature range of 1800 to 2200°F. A high efficiency recuperator can offer a heat recovery efficiency of 50% to 55% and deliver preheated air at about 1000°F. A regenerative burner system has an efficiency of 72% to 75% and delivers combustion air at about 1400 to 1500°F. The effect of this is to reduce fuel consumption by 30% for recuperators and by 40% for regenerators. This difference is significant when one considers effect of this on possible increases in production or melt rate. Most companies drive their furnaces hard to get 5% to 10% higher production and that results in higher flue gas temperature and severe damage to a recuperator. Push for higher production has resulted in higher input, higher flue gas temperatures (sometime far above the material design limitations) and often inefficient combustion that increases fuel consumption by a significant amount (10% to 20%), wiping out the expected benefit of the use of recuperators. The companies often neglect maintenance on recuperators and the end result is even more fuel consumption in furnaces.

However higher inputs and push for production does not have as bad an effect on regenerative systems as it does for recuperative systems since the regen systems use non-metallic parts with very high temperature capabilities.

The regen burners do present problems related to plugging of the bed when the furnaces are operated with dirty scrap, generate high percentage dross and generate soot particles. The problem is more severe during fluxing however an automatic control of the system allows by passing of the regenerative system when the user performs batch fluxing. Continuous fluxing, rarely used, could present a problem if the fluxes are highly corrosive to the ceramic materials.

It is necessary to clean the bed to avoid degradation of performance and reduction in firing rate that in turn would result in drop in melt rate and production. It is necessary to change the bed when it “plugs up”. A bed would remain clean for several months if the furnace operation is with clean charge material. However most users would charge some type of purchased scrap that may contain impurities. In this case it is necessary to change the bed periodically – ranging from once a week to once a month.

North American has developed a design of removable “magazine” that allows changeover of bed in about ½ hour during which time the furnace continues to run using bypass dampers and cold air. The end effect is higher energy use during this period however the furnace continues to run without loss of production. The bed needs to be cooled and cleaned by water spray which may take one shift or longer. In most companies a spare bed is maintained to replace a plugged bed while one of the beds is being cleaned and kept ready for the next changeover. There is very little, if any, attrition from the ceramic balls that are made out of alumina.

North American supplies the entire system that includes regenerative bed, burners, associated valves and linkages and furnace temperature controls. The representative mentioned that there was a lot of concern about the performance of solenoid valves used for the controls. However their experience has shown that the valves last for 4 to 5 million cycles, equivalent of 4 to 5 years and they have experienced life as long as 10 years in some installations. The North American system uses a fairly complex (compared to simple burner-recuperator system) control system to maintain the heat recovery and continuing efficient operation. It is necessary to use PLC controls and employ a technician or engineer with knowledge of PLC controls. The burner suppliers can provide periodic service on contract basis to maintain the system.

North American has installed more than 100 systems throughout the world and these include almost a dozen systems for various aluminum melting applications. They have observed that almost all new installations of aluminum melting furnaces use regenerative burners and they have not sold any conventional hot air burners for new aluminum melting furnaces. This clearly indicates that very few, if any, aluminum melters installed within the last 5 years or so use recuperators.

The cost of the North American system is slightly lower than that of Bloom system. It was explained that the payback for a new installation was 2 years or less when the gas prices were \$5.50 per million Btu. At today's gas process (from \$7 to \$10 or higher) the payback period should be between 1 to 1.5 years. It has been difficult to supply these burners for wide scale retrofit to existing furnace. However he feels that with increased cost and better economic justification tools required now, it will be possible to justify several more retrofits.

They believe that they have given lot of attention to NO_x reduction and turn-down for the burners and they have been fairly successful. Their efforts now are to reduce the size, improve performance and addressing the maintenance issues.

North American would be happy to supply customer list.

Conclusion and Comments:

Regenerative burners seem to be replacing conventional recuperator type waste heat recovery design. They offer an excellent opportunity to increase energy efficiency and furnace productivity simultaneously with acceptable pay back periods.

It is necessary to contact several users of regenerative burners, particularly those who have switched from recuperative systems to regenerative systems for their new furnaces or as retrofit, to get their side of the story and requirements. It would be very interesting to discuss their experiences on materials, maintenance, cost justification and views on comparison of recuperators vs regenerators.

It seems that the burner suppliers do not see materials R&D needs; however they can reduce the size of the unit significantly if we were to consider development of high heat capacity material or composite that can retain higher heat per unit volume. Right now the main objection to the use of regenerative burners in existing installation is its size and cost. Often the two or four burners require as much room as the furnace footprint itself. Recuperators are large but they sit on the top of a furnace; however, the regenerators have to be located on the side of the furnace and require additional “footprint” space.

Seco Warwick Corporation

Seco Warwick is a major supplier of furnaces to the aluminum industry world wide. They are considered as a leader in design and building of all types of aluminum melting furnaces including large reverberatory furnaces used by primary and secondary aluminum industry companies.

They provided information on their experience and opinion about the use of recuperators to recover flue gas heat for combustion air preheating or any other type of use within the aluminum melting facility.

They mentioned that the U.S. customers hardly request use of a recuperator for melting furnaces. On the other hand they get specifications for furnaces to include waste heat recovery and combustion air preheating for the melting furnaces. They have supplied 20 to 30 furnaces during the last 5 years in Asia, Middle East, and Far East including China with heat recovery systems. These heat recovery systems include recuperators with tubular convection heat exchanger design as well as regenerative burner systems. These customers tend to be more careful in operation and maintenance of the furnaces and use advanced controls to operate and monitor furnace performance. The general trend is to use regenerative burners since most customers use some type of fluxing or variable quality (often oily) scrap that causes problems in use of recuperators.

Although the regenerative burners are also prone to similar problems, it is easier and relatively inexpensive to maintain this type of heat recovery devices as opposed to convection (tubular) heat exchanger type recuperators. They have not supplied one recuperator for a U.S. customer

during the last 20 years! On the other hand they have quoted and supplied a number of jobs (5 to 6) to U.S. customers during the last 2 years with regenerative burners.

The regenerative burners use ceramic pebbles or balls and their inner surfaces are insulated with non-metallic materials. As a result they can withstand much higher temperatures without damage to the heat transfer matrix and do not require major parts maintenance. The maintenance or cleaning process is relatively simple and can be simplified by using a “spare” “magazine” of heat transfer surfaces. The surfaces also do not degrade the heat transfer performance. However they do plug up when the flue gases contain solid particles and other contaminants. The presence of organic or volatiles does not degrade performance since they tend to combust when hot air is introduced in the regenerator. Higher temperatures generated from the burning have very little, if any effect on the materials since they are made out of higher temperature ceramic materials such as alumina or in a few cases silicone carbide.

In North America two companies supply almost all regenerative burner systems. They are: North American Manufacturing Company out of Cleveland, OH. and Bloom Engineering out of Pittsburgh, PA. Recently Hauck Burner Company is experimenting with a rotary wheel type regenerative device that has been used in Europe for aluminum melting furnace applications. However at this time they do not have any U.S. installation. In the past a British Company (Hot Works) has supplied regenerative burners for U.S. companies; however, they have not been very active in the US. They are major suppliers in Europe. All of these companies are now active in the international market and have been installing the regenerative heat recovery system on new furnaces as well, in a few cases, as retrofits.

In Seco Warwick’s opinion the regenerative systems are very attractive since they have less moving parts, they offer much higher efficiency, tolerate higher temperatures and temperature excursions if any, and do not pose the problems of leaky tubes resulting in rich combustion in the burners.

Seco Warwick likes the “forgiving” features of these systems. For example the regenerative burners do plug up when the flue gases contain particulates etc. but this does not require extensive maintenance process and the system can be put back in operation in a matter of “minutes”. In his opinion it is not necessary to stop production during replacement time. The only loss is loss of efficiency for a relatively short duration.

In their opinion, use of recuperators on aluminum melting system would not come back and there will be a trend towards retrofitting of regenerative systems on existing furnaces.

Regarding the research needs, they do not think that there is any major area that needs material development program. However they do see a need for development of new techniques in controls and construction to reduce the size of these units so that they can be used as a retrofit for existing furnaces.

Conclusion:

Seco Warwick has not supplied a single furnace in the US with recuperator installation in the last 20 years. The current trend is to use regenerative burner systems and they see this as a future trend. They advised us to contact regenerator suppliers to get more information related to the materials or any other needs for the regenerative burner technology. He personally cannot identify any opportunities for materials development in current designs.

Thermal Transfer Corporation

Thermal Transfer is a division of Hamon Corporation with head quarters in Brussels, Belgium. The Thermal Transfer division is a major supplier of specialty design heat transfer and heat recovery equipment. Their heat recovery equipment includes convection and radiation recuperators, gas coolers, process heaters etc. Much of this equipment operates in some of the most aggressive and difficult environments in industry, including steel (and other primary metals), refinery, petrochemical, glass, waste incineration, and carbon black. The equipment design requires operations in hard-to-handle applications - dirty gases, high temperatures, corrosive / erosive environments, and any other application that requires a specialized, non-standard equipment design.

Historically the division in the US has been active in the aluminum and glass industries for recuperation of heat from high temperature contaminated gases.

The following section gives their response to specific questions we asked them.

1. What are commonly used designs and what are the positive and negative features of each?

Thermal transfer offers several different designs and configuration of heat exchangers. Some of the designs include several tubular design recuperators with co-current, counter current, and cross flow configurations for the aluminum industry. The radiation type designs are supplied to the glass industry, steel industry and other higher temperature applications. According to Thermal transfer radiation recuperators are not well suited for heat recovery from aluminum melting furnace exhaust gases. The tubular recuperators are compact, more efficient and offer the best service for flue gases below 2000°F. Thermal transfer design uses centrifugally cast tubes that offer larger wall thickness and little welding that may result in weak points in the tube service. The tubular recuperators are easy to clean when used in environment that contains particulates. They can be used for flue gases containing particulates, corrosive gases and other contaminants. With proper design (tube size, tube spacing, tube material etc.) they offer long life and ease of maintenance (tube cleaning, repairs, replacement etc.). For aluminum applications corrosion from salts is detrimental to tubes however with air flow inside the tubes and gas flow outside the tubes and proper control of the gas temperature to keep them below the tube material design temperature, it is possible to achieve long (3 to 5 years) life for the front tubes. Life of the tubes in the back is all over the map, in most cases considerably longer than 3 to 5 years, usually 5 to 7 years or as long as 10 years.

2. What alloys are used or offered for the recuperator tubes (or metallic plates)?

Thermal transfer uses a large variety of alloys for different designs. The alloy selection depends primarily on temperature and then on corrosion, mechanical loading (internal air pressure), and other factors that affect the tube life. In aluminum applications where there is a possibility of high temperature and corrosion potential, Thermal Transfer uses cast alloys such as HT, HE, HL etc. For more critical applications they have used 50/50 (Chrome. Nickel) alloys. The alloy selection depends on economic consideration and final air preheat temperature.

3. Have you done any CFD modeling of the air flow in the recuperator tubes and/or the flue gas flow across the tubes? If yes, would you like to share the results with the Oak Ridge National

Laboratory (ORNL) on a confidential basis for review and possible help? If not, would you be interested in working with the ORNL if they were to do this modeling?

Thermal transfer in USA does not have CFD modeling capabilities. All of their designs have evolved over more than 40 years. The design is modified based on in-house testing, rule of thumb developed based on testing and field experience and test data collected during solving the problems. There are no results to share with ORNL.

They are interested in performing CFD analysis but the cost for software, training, and trial-error steps seem to be cost prohibitive. They may discuss working with ORNL to pursue CFD analysis activities however several issues related to confidentiality, sharing of proprietary drawings etc. need to be discussed. Such discussions would require approval of the management. This can be pursued after further discussions related to details of working relationship etc.

4. How many recuperators are you selling to different industries? Are you supplying the replacement tubes to the recuperator user? In any case how many replacement tubes are sold annually?

The number of recuperators sold varies considerably from year to year. Thermal transfer has supplied over 2000 tubular design recuperator units to various industries over the last 30 years. However during the last few years they sell 20 to 30 units in a good year and 5 to 10 when the industrial business activities are very slow. Right now they are not seeing any activity in sales of tubular recuperators for aluminum industry. The existing orders are for USA and mostly overseas, in various other industrial applications such as DRI plants (steel industry) for gas cooling, steel industry for combustion air preheating, thermal oxidizers for heat recovery. The overseas activities, particularly in China is considerably more than that for USA industries.

The tube replacement business varies and in many cases the customers purchase their own units tubes from various other sources. This business is very small percentage of the total business.

5. Can you identify companies that are using recuperators so that ORNL can ask them to participate in our project?

Thermal Transfer has supplied units to more than 100 companies in the US and overseas. They would not want to release names of all of their customers however they would be glad to supply a list of selected customers. They have promised to send a list within a week or so.

6. Would you (the suppliers) be interested in working with us on the project?

Thermal Transfer would be interested in working with ORNL with appropriate confidentiality and proprietary information protection to develop potential heat recovery applications in the aluminum industry. They would like to consider what they could gain vs. the time and other resources spent on the collaborative efforts. They are willing to pursue this further.

Conclusion:

Thermal Transfer has been a major supplier of recuperators for aluminum melting furnaces in the past. However during the last few years they have not supplied significant numbers (if any) of recuperators for aluminum melting furnaces. They do not believe that new materials could help in solving the current problems related to operational issues and charge material quality related

issues can be addressed by using newer materials. They do not use CFD analysis and do not see any need to devote resources for developing CFD analysis capability. However they would; be happy to discuss possibilities of working with ORNL if it does not require significant allocation of funds and other resources. They would also like to continue participating in any activities that help and promote use of waste heat recovery in aluminum melting and other applications.