Very High-Temperature ODS Alloy Heat Exchangers for Solid-Fuel Thermal Systems

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INTRODUCTION

In 1991, the U.S. Department of Energy (DOE) started the Combustion 2000 program, which is designed to work with industry in the development of an ambitious high-efficiency coal-fired power plant technology called the high-performance power system, or HiPPS, concept. This type of plant will use a combined cycle involving a typical steam turbine along with an indirectly fired turbine cycle using very-high-temperature but low-pressure air as the working fluid. The goals for the HiPPS system are 47% efficiency, with only one-tenth of the particulate, SO_x, and NO_x emissions allowed under the New Source Performance Standards, while reducing the cost of electricity (COE) by 10%. The Energy & Environmental Research Center (EERC) worked with a team led by United Technologies Research Center (UTRC) in the development of this system.

The heart of the UTRC HiPPS system is a high-temperature heat exchanger (HTHX) to produce clean air to turn an aeroderivative turbine. The overall system design is like that of a combined-cycle gas turbine system, except that a pulverized coal (pc)-fired furnace containing the HTHX is used to preheat the air entering the gas turbine. To achieve the highest temperatures and efficiencies of up to 55%, a gas-fired duct burner can be used to top the gas entering the turbine to reach 2600°F and 250 psi. Because of the extremely high temperatures necessary, only advanced oxide dispersion strengthened (ODS) alloys or ceramics can be used to carry the high-temperature gases. ODS alloys typically contain 0.5% of an oxide such as yttria dispersed through the material. The oxide particles help to pin grain boundaries, reducing their ability to creep at high temperatures. Early in the program, the EERC and UTRC determined that the current state of the art for ceramic heat exchangers was insufficient to use in reaching near-term objectives. Therefore, UTRC turned primarily to the ODS alloys because of their superior high-temperature creep resistance as compared to superalloys.

Pilot-Scale Testing of the HTHX

To protect the alloys from corrosion by the products of coal combustion, UTRC designed the HTHX to include panels of corrosion-resistant ceramic between the alloy heat exchanger tubes and the coal flame. The "tubes in a box" design is shown in Figure 1.

The EERC tested the HTHX in the slagging furnace system (SFS) which was designed and constructed during the program. The SFS is designed to heat the HTHX under flowing slag conditions so that it can produce process air at 1800˚F and 150 psig. A schematic of the system is shown in Figure 2. The SFS is designed for a maximum furnace exit temperature of 2900°F, but is typically run at 2750°F at the exit in order to maintain desired slag flow while extending the furnace lifetime. It has a nominal firing rate of 2.5 million Btu/hr and a range of 2.0 to 3.0 million Btu/hr using a single burner. The design is based on a bituminous coal (Illinois No. 6)

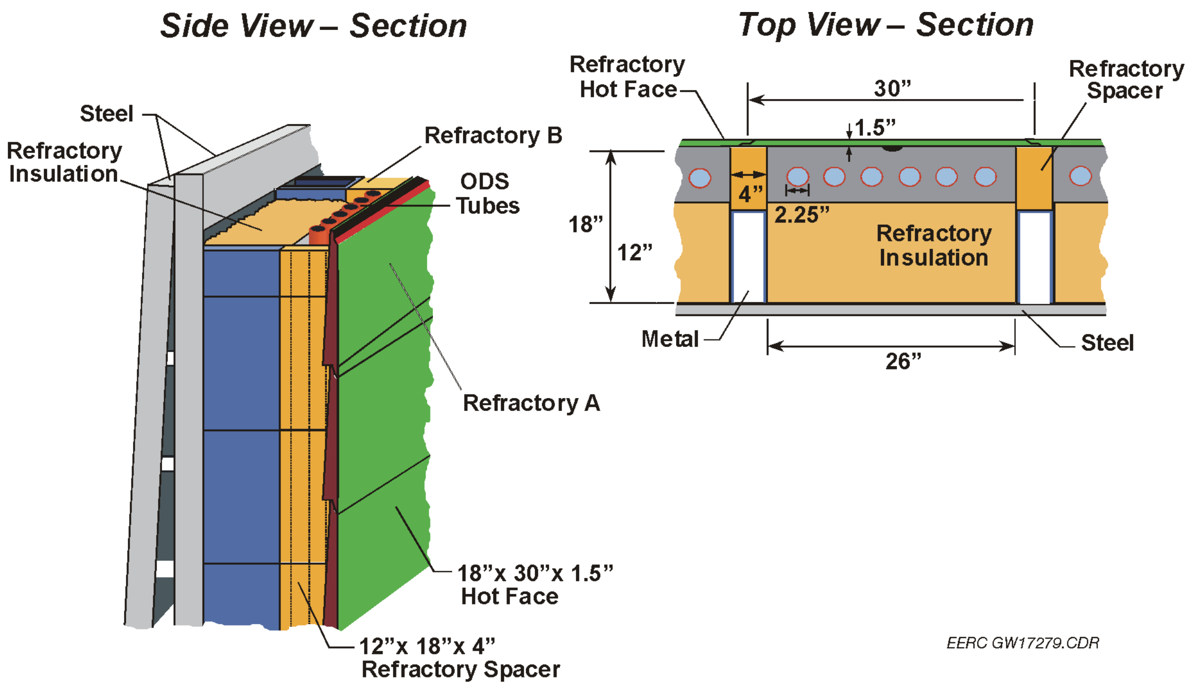

Figure 1. The UTRC high-temperature heat exchanger design.

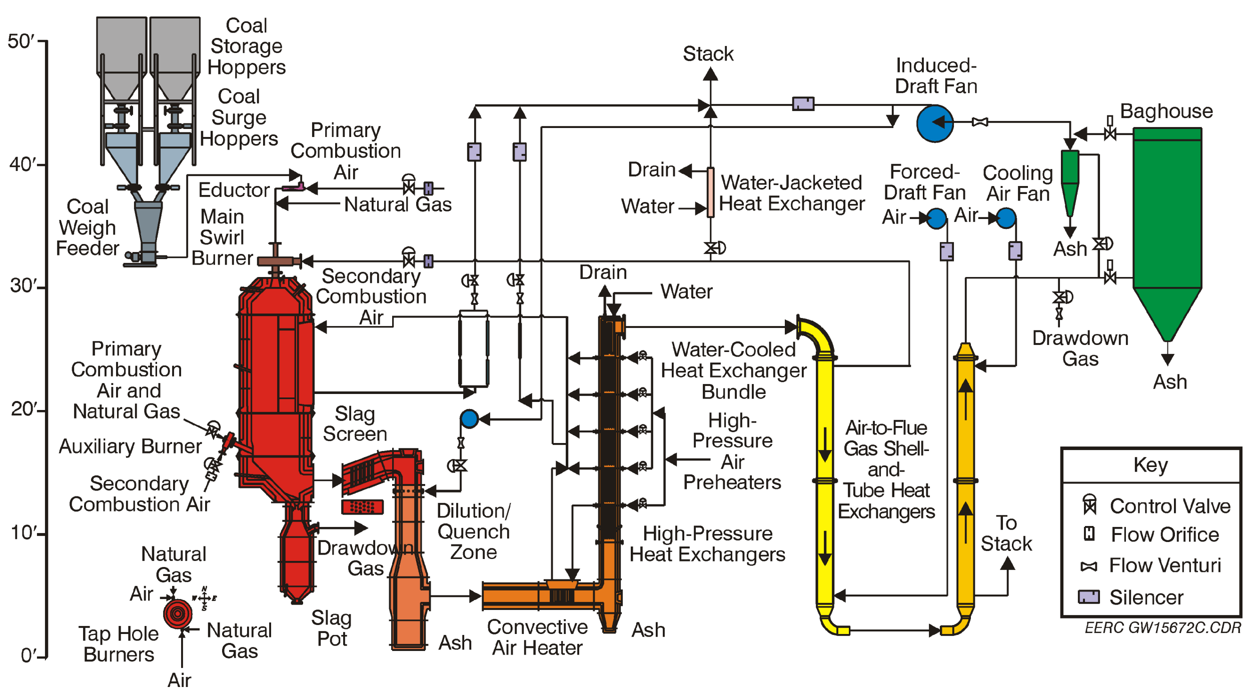

Figure 2. Schematic of the EERC high-temperature advanced furnace (HITAF) system

and a nominal furnace residence time of 3.5 s. Resulting flue gas flow rates range from roughly 425 to 640 scfm, with a nominal value of 530 scfm based on 20% excess air. Firing a low-rank coal or cofiring with biomass will increase the flue gas volume, decreasing residence time to roughly 2.7 s. However, the high volatility of the low-rank fuels will result in high combustion efficiency (>99%). The EERC oriented the furnace vertically (downfired) and based the burner design on a swirl burner currently used on two EERC pilot-scale pc-fired units that are fired at 600,000 Btu/hr. The furnace dimensions are 47 in. (119 cm) inside diameter (i.d.) by roughly 18 ft in length. It is lined with three layers of refractory totaling 12 in. thick. The inner layer is composed of an alumina castable, developed by the EERC in cooperation with the Plibrico Company, that has been shown in laboratory tests to be extremely resistant to slag corrosion.

A key design feature of the furnace is accessibility for installation and testing of a large HTHX test panel for testing material lifetimes and heat exchange coefficients. The HTHX is 1 × 6 ft. This size was based on manufacturing constraints identified by UTRC, which designed and built it. The HTHX is composed of three vertically oriented 2½”-diameter tubes made of MA754, a nickel–chrome ODS alloy. Air to be heated by the HTHX panel is provided by an existing EERC air compressor system having a maximum delivery rate of 510 scfm and a maximum stable delivery pressure of 275 psig. It is heated from 1000°F to as much as 1800°F as it passes through. A tie-in to an existing nitrogen system was also installed as a backup to the existing air compressor system to prevent the panel from overheating in the event of a power outage.

As the hot combustion gases leave the combustor, they pass through a slag screen to remove the entrained ash as a nonleachable slag and reduce deposition on the convective air heater (CAH). It removes approximately 65% of the particulate matter from the gas stream. As the hot combustion gas leaves the slag screen, it is quenched with recirculated flue gas to 1850°F in order to make the ash less sticky and reduce deposition on the CAH. The quench zone is the only region in the furnace where hard ash deposits form, but they are easily removed by knocking them into a hopper at the bottom of the zone. The gases then pass over the CAH which is used to heat air from 1000° to 1300°F. The hot combustion gases then flow through a series of heat exchangers and, finally, a baghouse on the way to the system stack.

The HiPPS program testing of the UTRC HTHX in the slagging furnace system showed that it performed well, typically producing 1800°F air at 150 psig for over 2000 hours of operation. For a short duration, air up to 2000°F was produced which is believed to be a record for a coal-fired system. However, the ceramic panels were prone to failure through thermal shock and were significant impediments to heat flow. To determine if the HTHX could be operated without the ceramic panels, the EERC performed laboratory tests to determine if the MA754 alloy could be exposed directly to the products of coal combustion. Figure 3 shows the surface recessions of coupons of the MA754 exposed to Illinois No. 6 coal ash and flowing gas at 1832°F and 2100°F. The data indicate that as long as the surface temperature of the alloy is kept below the solidus temperature of the fuel slag, corrosion rates of the MA754 could be commercially acceptable and the bare alloy tubes could be directly exposed to the products of coal combustion. Although the Combustion 2000 program has ended, DOE is continuing the development of the very-high-temperature heat exchanger concept, both through funding the

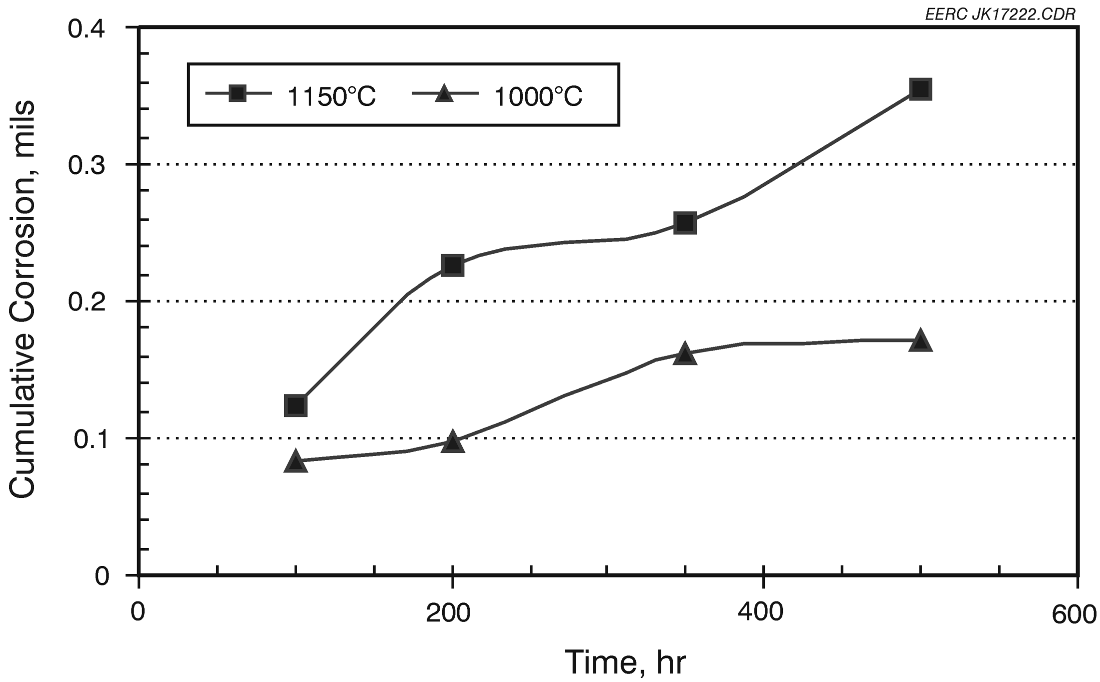

Figure 3. Surface recession rates for MA754 exposed to Illinois No. 6 ash and flowing gas.

EERC directly for continued testing and through other programs such as the DOE Vision 21 program.

HTHX Operation

Initial tests of the bare-tube configuration showed that heat exchange coefficients were so high without the ceramic panels that not enough cooling air could be provided with the existing equipment. Therefore, the initial tests were done while firing the SFS at much lower rates than the normal operation as changes were made to the system to allow firing at higher rates while still cooling the surface temperature of the alloy to 2000˚F. The changes culminated in reducing the surface area of the exposed tubes by encasing the bottom half of the HTHX in alumina insulation and refractory. The HTHX is typically operated with process air flow rates of 350 to 365 scfm at 150 psig. Inlet process air temperatures are 1000° to 1025°F and alloy tube surface temperatures 1385° to 2010°F. The low end of the alloy tube surface temperature range represents the back side of the tubes at the process air inlet, with the high end of the range representing the front side of the tubes at the center of the HTHX. Process air temperature at the outlet ranged from 1410° to 1580°F. Heat recovery rates ranged from 206,000 to 241,000 Btu/hr.

One of the first issues to work out with the bare-tube design was whether or not hot spots, possibly leading to strong thermal stresses, developed in the structure because of its exposure directly to the coal flame. Instrumenting the HTHX with numerous thermocouples is not sufficient in looking for these hot spots. Therefore, the EERC requested assistance from the NASA Johnson Space Center in the form of an infrared camera and an engineer to operate it.

Given the success of that testing in June of 2001, the EERC has recently purchased its own camera. Figure 4 shows an infrared (IR) image of the tubes while firing natural gas along with the calculated temperature distribution along the surface of the middle tube. The data show that no hot spots developed on the tubes because of incomplete air distribution and that circumferential and axial temperature distributions were smooth and should not cause undue stresses in the tubes.

The longest test of the HTHX while firing coal at the maximum level was made in November and December of 2001. The heat recovered by the HTHX decreased as a function of time, nominally from 241,000 to 209,000 Btu/hr, or 13%, during the first 70 hr of coal firing. Heat recovery appeared to be stable during the last 30 hr. Therefore, if adequate process air were available and half of the HTHX was not insulated, the resulting heat recovery rate would be 410,000 to 420,000 Btu/hr at a nominal furnace temperature of 2800° to 2830°F.

HTHX heat removal data as a function of furnace temperature are summarized in Figure 5 on an equivalent-surface-area basis for select test periods completed in 1999 and 2000 and all of the test periods completed in 2001. The data for the June, August, and November/December 2001 tests of the bare-tube design are represented by open symbols and are connected by lines for natural gas-fired tests. Data resulting from coal-fired tests are simply open symbols. The 2001 data are compared to data in the lower right of the graph, represented by closed symbols, for tests performed in 1999 and 2000 in which the original ceramic panels were in place. The data clearly show that for a given furnace temperature, removing the ceramic panels from the heat exchanger increases the heat removal rate by nearly a factor of five. This means that the heat exchanger

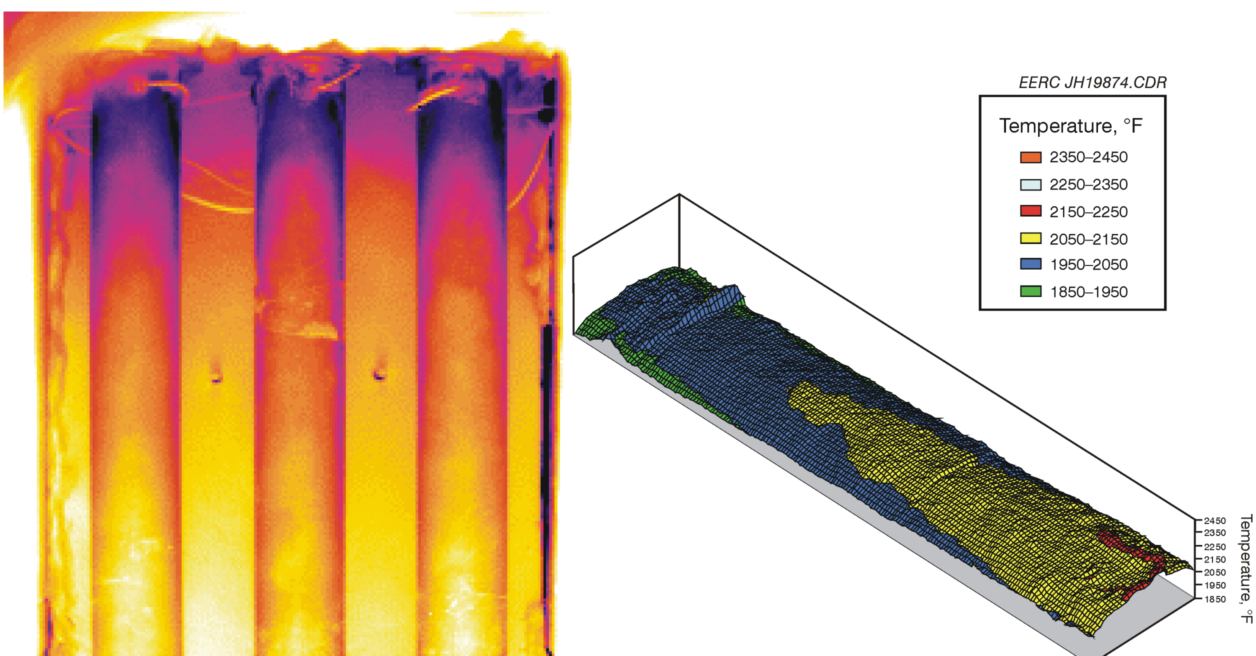

Figure 4. Infrared image and temperature distribution of the upper portion of the middle tube in the HTHX while firing on natural gas.

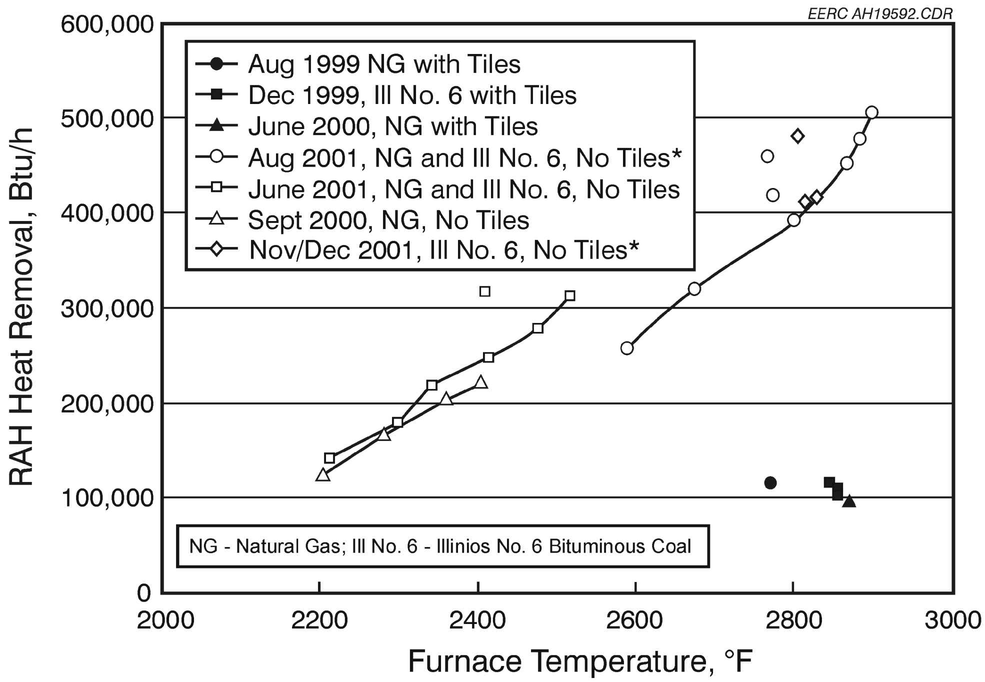

Figure 5. Heat removal as a function of furnace temperature on an equivalent surface area basis.

could be as small as one-fifth of that originally proposed. Factoring in the price reduction by not requiring the panels and the unprotected heat exchanger panel could cost as little as one-tenth as much as the original tubes-in-a-box design.

Measurements of the MA754 tube diameters after coal firing indicated no recession or significant dimensional variations compared to the measurements before the test. Ash depositing on the tube forms a sintered powder layer of fly ash between a brittle slag layer and the alloy surface. Total thickness of the sintered powder is several tenths of a millimeter, while the slag layer varied from 2 to 5 millimeters thick. The lightly sintered nature of the inner layer indicates that its corrosivity toward the alloy should be low, while the slag layer forms running drips, indicating that it has reached its maximum thickness and begun to flow off of the tube. The brittle fused slag/sintered ash layer was easily removed from the alloy surfaces, indicating little interaction between the alloy and the ash.

The development of the sintered ash overlain by the slag layer is the primary reason for the 13% decrease in heat recovery during coal firing. This illustrates one of the main advantages to operating the HTHX at such high temperatures that the ash develops only a very thin layer before becoming molten and flowing off. In essence, the tubes become self-cleaning, and the 13% drop is less than one-third of the typical 50% drop seen when much thicker sintered ash deposits develop on heat-transfer surfaces. It is the insulating effect of the ash deposits that causes the need for up to twice as much heat exchange surface to be installed in a furnace than would be required if the ash did not insulate the tubes. Given the self-cleaning nature of the thin deposits forming on the bare-tube HTHX, the excess surface area needed would only be approximately 20% as compared to 100% excess for conventional heat exchangers operating at ash-sintering temperatures.

Air-Cooled Probe

In order to perform detailed analyses of the ODS alloys after exposure in the SFS, short disposable air-cooled probes are made and inserted into the slagging zone while firing on coal. Two alloys have been tested in the probes to date. They include the MA754 alloy which was used for construction of the HTHX and the MA956, an iron–chrome–aluminum ODS alloy that forms a protective alumina skin if prepared correctly. In one such test, an MA754 probe was left in place for nominally 130 hr of coal firing prior. Alloy surface temperature was controlled at nominally 1780˚ to 2000˚F as a function of probe insertion depth and a process air flow rate of 95 to 100 scfm. Measurements showed an average surface recession of approximately 60 μm (0.002 inches)/130 hours, or 4 mm (0.2 inch)/year. The end of the probe that was not efficiently cooled had melted, but corrosion was minimal right up to the point where the tube did melt. The slag layer that had formed on the surface of the tube during the test was only approximately 1.5 mm (0.06 in.) thick and composed of three layers. A schematic of the layers is shown in Figure 6. During cooling, the slag layer spalled off of the tube, indicating that it was not intimately bonded to the tube. The innermost layer was sintered and approximately 50–250 μm thick. The fact that it was sintered implies that the ash would be relatively solid; therefore, corrosion of the alloy by this inner layer of ash would be low.

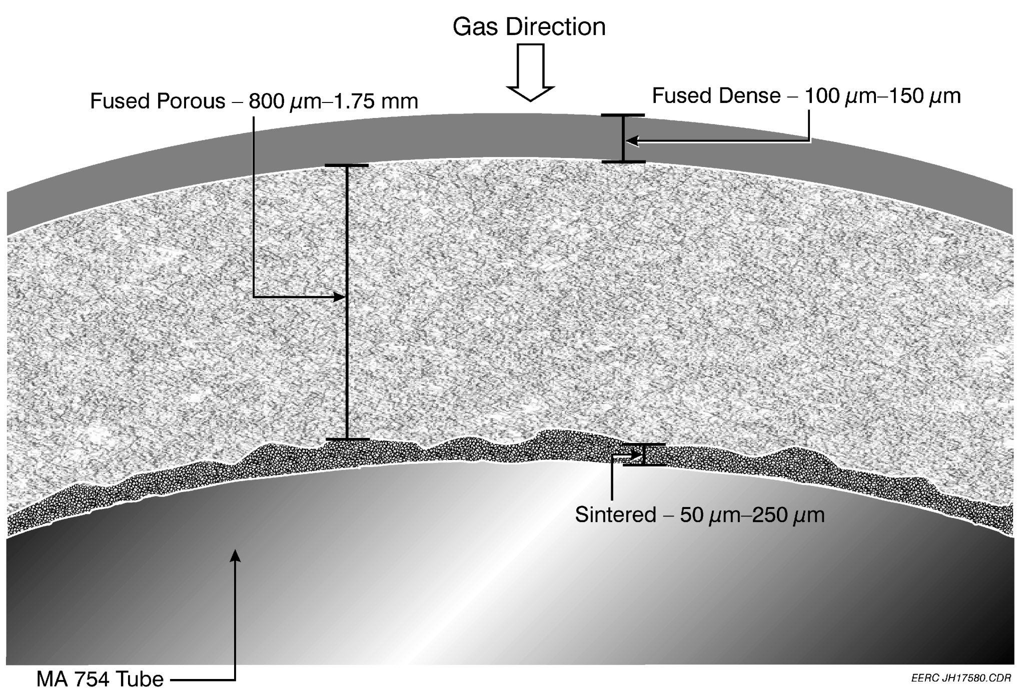

Figure 6. Schematic of the slag layers that formed on the cooled MA754 probe exposed directly to the coal flame in the SFS.

On top of the sintered layer was a fused but porous layer approximately 800 to 1750 µm thick. The fact that the layer was fused indicates that it would have a high thermal conductivity, but the porous nature indicates that it would not be flowing and so would provide a relatively permanent corrosion protection layer. The outer layer was fused and dense. It was approximately 100 to 150 µm thick. Its density indicates that it was likely molten at temperature and would, therefore, be constantly flowing off, preventing any greater buildup of ash. In another SFS test performed with Illinois No. 6 coal, a similar probe, this time made with the iron-based ODS alloy MA956, was exposed to flame conditions for 100 hours while the surface was cooled to nominally 2000˚F. However, a loss of cooling air occurred shortly into the test so that the alloy reached temperatures as high as 2600˚F for a period of 2 hours. Because of this loss of cooling, the ash in contact with the probe fused into a solid mass. Fortunately, the MA956 alloy has a higher melting point than the MA754, and it also forms an alumina surface scale which protected it from the fused slag attack. Figure 7 shows a scanning electron microscopy (SEM) photograph of a cross-sectioned MA956–fused slag interface. It shows the absence of any porosity in the slag, indicating it had reached the fusion temperature and a relatively uniform 3–5-micron dark gray alumina layer on the surface on the alloy. This oxide layer protected the underlying alloy from direct attack by the slag. Between the alloy surface and the fused slag, there is indication of an iron–aluminum transition layer tending toward a calcium–aluminum silicate matrix with scattered iron oxide-rich and iron–calcium silicate crystals.

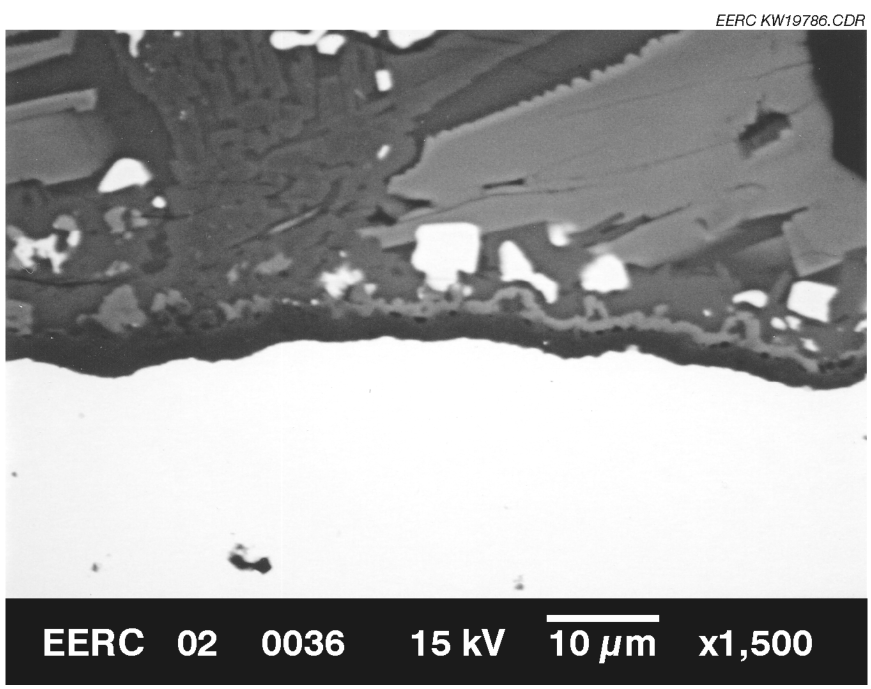

Figure 7. Cross section of the MA956 alloy–slag interface showing the fused slag and protective alumina layer between the alloy and slag.

One of the problems that develops in the use of ODS alloys can be seen by the amount of damage done to the alloy during the process of welding such as that shown in Figure 8, which is a SEM photograph of the weld of a thermocouple to the MA956 surface. The Inconel thermocouple casing (light grey toward the top) and the nickle–chromium welding material (darker grey between thermocouple and alloy) can be seen toward the top of the figure. The damage is evident in the excessive porosity in the alloy as indicated by black dots within the light gray alloy at the bottom of the image. This demonstrates the poor performance of the alloy during welding. Both the EERC and Special Metals Corporation are currently working on separate but cooperative DOE-funded projects to develop methods of joining the MA956 alloy without conventional welding.

Effect on Cost of Electricity

The use of the bare tubes in the heat exchanger would not have a significant effect on the overall efficiency of a power system as compared to the tubes-in-a-box design. While the radiant heat-transfer rates to the tubes would increase, the air outlet temperature is still determined by the maximum tube wall temperature, which is governed by stress and corrosion considerations. Thus no changes are anticipated in the estimated 47% higher heating value (HHV) efficiency of the bare tube HTHX using a state-of-the-art turbine as compared to the tubes-in-a-box HTHX. Figure 9 shows the efficiencies of a current pc-fired plant as compared to four different bare-tube HiPPS configurations, an integrated gasification combined cycle (IGCC) plant using an H class turbine, and a natural gas-fired combined-cycle plant using an F class turbine. The four HiPPS configurations include using 1) currently installed turbine technology, 2) state-of-the-art turbine

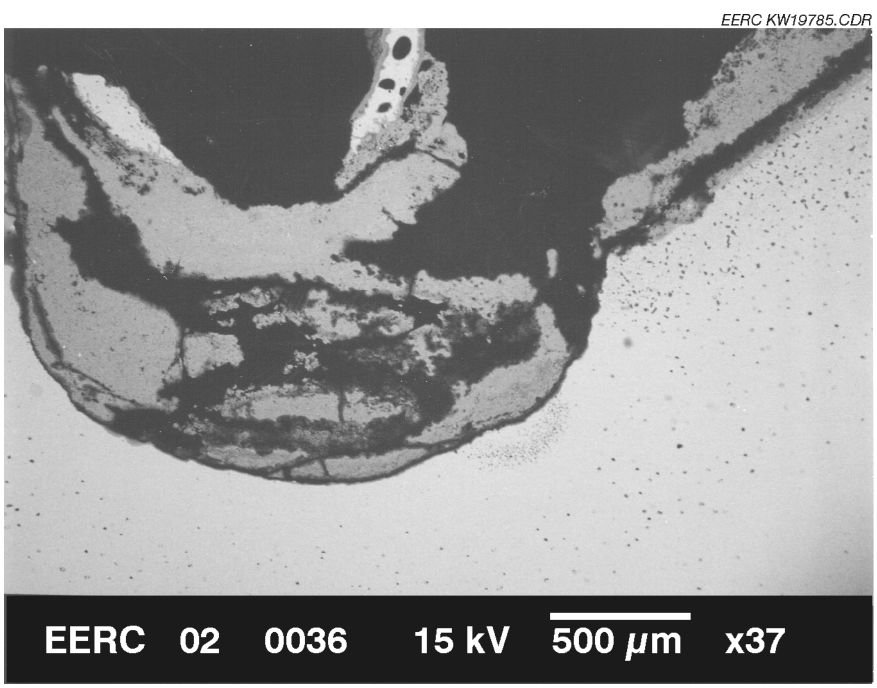

Figure 8. Pore formation in the MA956 alloy caused by melting during welding.

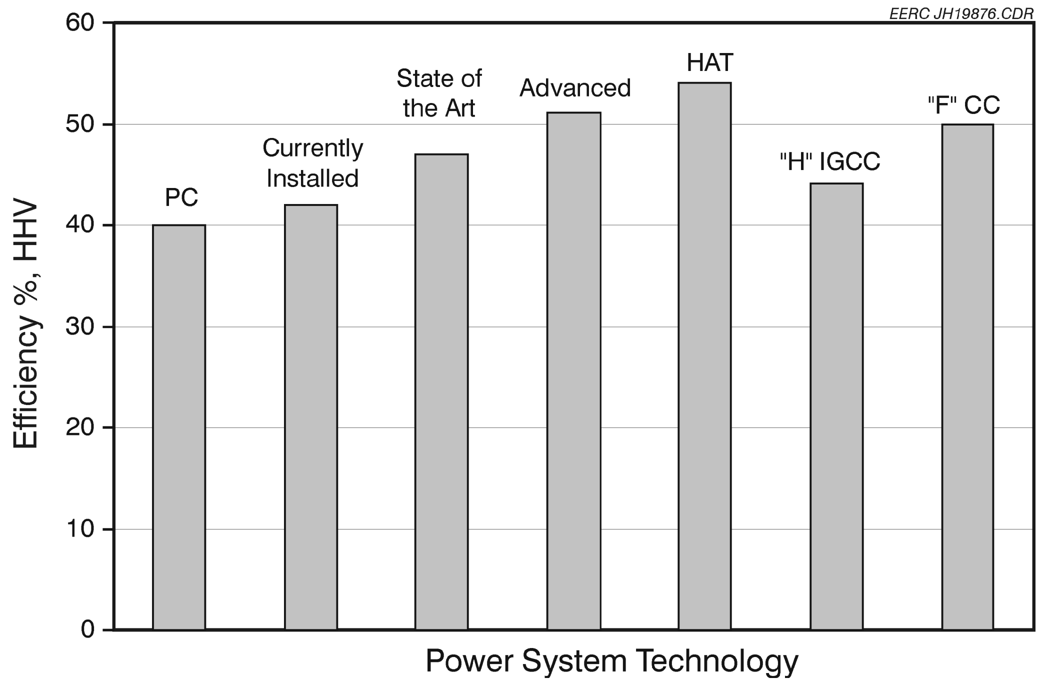

Figure 9. Higher heating value efficiencies for pc, HiPPS, IGCC, and natural gas-fired combined-cycle plants.

technology, 3) near-term advanced turbine technology, and 4) an advanced humid air turbine (HAT). The data show that by using state-of-the-art turbine technology, the efficiency of a HiPPS system employing a HTHX is similar to that for IGCC or gas-fired combined-cycle plants. Using advanced turbines, efficiencies can be even higher.

Although efficiencies for HiPPS plants rise with the turbine technology employed, the COE can actually drop, assuming existing or projected prices for the systems. Figure 10 shows the relative COE for a modern pc plant (assigned a relative cost of unity) as compared to that for the four HiPPS systems (with two HTHX process air temperatures for the currently installed technology) and the IGCC and natural gas-fired plants using a 20-year levelized cost of coal of $0.99/million Btu and for gas of $3.29/million Btu. These data show that the lowest relative COE for these systems is for a HiPPS using a HTHX producing 2100˚F process air and a current technology turbine. The second lowest is for a similar system producing 1700˚F air. This implies that a cost-competitive HiPPS system could be built with available HTHX and turbine technology.

Acknowledgments

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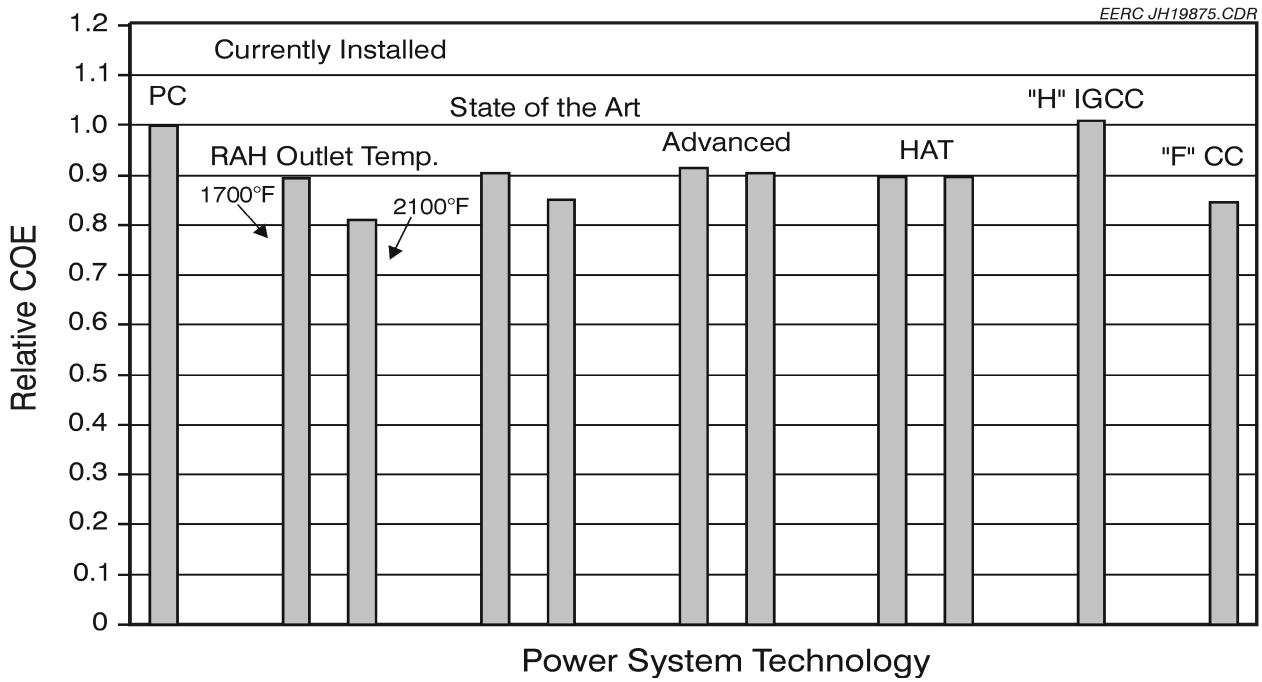

Figure 10. Relative cost of electricity for pc, HiPPS, IGCC, and natural gas-fired combined-cycle plants.