TASK 3.3 – HIGH-TEMPERATURE HEAT EXCHANGER TESTING IN A PILOT-SCALE SLAGGING FURNACE SYSTEM

Final Topical Report

Prepared for:

U.S. Department of Energy
National Energy Technology Laboratory
PO Box 10940, MS 922-178C
Pittsburgh, PA 15236-0940

Cooperative Agreement Contract No. DE-FC26-98FT40320--09

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ACKNOWLEDGMENT

This report was prepared with the support of the U.S. Department of Energy (DOE) National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-98FT40320. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors(s) and do not necessarily reflect the views of DOE.

TASK 3.3 – HIGH-TEMPERATURE HEAT EXCHANGER TESTING IN A PILOT-SCALE SLAGGING FURNACE SYSTEM

ABSTRACT

The University of North Dakota Energy & Environmental Research Center (EERC), in partnership with United Technologies Research Center (UTRC) under a U.S. Department of Energy (DOE) contract, has designed, constructed, and operated a 3.0-million Btu/hr (3.2×10^6 kJ/hr) slagging furnace system (SFS). Successful operation has demonstrated that the SFS meets design objectives and is well suited for testing very high-temperature heat exchanger concepts. Test results have shown that a high-temperature radiant air heater (RAH) panel designed and constructed by UTRC and used in the SFS can produce a 2000°F (1094°C) process air stream. To support the pilot-scale work, the EERC has also constructed laboratory- and bench-scale equipment which was used to determine the corrosion resistance of refractory and structural materials and develop methods to improve corrosion resistance.

DOE projects that from 1995 to 2015, worldwide use of electricity will double to approach 20 trillion kilowatt hours. This growth comes during a time of concern over global warming, thought by many policy makers to be caused primarily by increases from coal-fired boilers in carbon dioxide (CO₂) emissions through the use of fossil fuels. Assuming limits on CO₂ emissions from coal-fired boilers are imposed in the future, the most economical CO₂ mitigation option may be efficiency improvements. Unless efficiency improvements are made in coal-fired power plants, utilities may be forced to turn to more expensive fuels or buy CO₂ credits.

One way to improve the efficiency of a coal-fired power plant is to use a combined cycle involving a typical steam cycle along with an indirectly fired turbine cycle using very high-temperature but low-pressure air as the working fluid. At the heart of an indirectly fired turbine combined-cycle power system are very high-temperature heat exchangers that can produce clean air at up to 2600°F (1427°C) and 250 psi (17 bar) to turn an aeroderivative turbine. The overall system design can be very similar to that of a typical pulverized coal-fired boiler system, except that ceramics and alloys are used to carry the very high-temperature air rather than steam. This design makes the combined-cycle system especially suitable as a boiler-repowering technology. With the use of a gas-fired duct heater, efficiencies of 55% can be achieved, leading to reductions in CO₂ emissions of 40% as compared to today's coal-fired systems.

On the basis of work completed to date, the high-temperature advanced furnace (HITAF) concept appears to offer a higher-efficiency technology option for coal-fired power generation systems than conventional pulverized coal firing. Concept analyses have demonstrated the ability to achieve program objectives for emissions (10% of New Source Performance Standards, i.e., 0.003 lb/MMBtu of particulate), efficiency (47%–55%), and cost of electricity (10%–25% below today's cost). Higher-efficiency technology options for new plants as well as repowering are important to the power generation industry in order to conserve valuable fossil fuel resources, reduce the quantity of pollutants (air and water) and solid wastes generated per MW, and reduce the cost of power production in a deregulated industry.

Possibly more important than their potential application in a new high-temperature power system, the RAH panel and convective air heater tube bank are potential retrofit technology options for existing coal-fired boilers to improve plant efficiencies. Therefore, further development of these process air-based high-temperature heat exchangers and their potential for commercial application is directly applicable to the development of enabling technologies in support of the Vision 21 program objectives.

The objective of the work documented in this report was to improve the performance of the UTRC high-temperature heat exchanger, demonstrate the fuel flexibility of the slagging combustor, and test methods for reducing corrosion of brick and castable refractory in such combustion environments. Specific technical issues of interest included measuring the effects of coatings on heat transfer in the RAH, determining the general impact of firing a lower-iron bituminous coal on the operation of the RAH panel and SFS, and the development of ways to treat slag and refractories to decrease corrosion rates.

The scope of work consisted of two tasks. Task 1 involved the completion of three test periods and nearly 4 weeks of pilot-scale SFS operation. In addition to the pilot-scale tests, bench-scale tests (Task 2) of methods to increase the corrosion resistance of refractories and reduce the corrosiveness of coal slag were performed with the dynamic slag application furnace (DSAF). These tests were complemented with determinations of appropriate coal additives that could be used to decrease the slag corrosion rates either by increasing the slag viscosity (but still keeping it flowable) or by changing its ability to dissolve the refractory.

On the basis of RAH heat-transfer data obtained during the three test periods completed, no conclusion can be drawn concerning the use or nonuse of a coating on the cavity side of the RAH ceramic tiles to improve cavity-side heat transfer.

Firing a low-iron bituminous coal did not have any detrimental impact on the performance of the RAH panel. In fact, RAH panel heat transfer was greater when the low-iron bituminous coal was fired because of its overall higher quality and the resulting stable operation of the pilot-scale SFS in general. Problems encountered with slag screen plugging were readily mitigated by injecting a small amount of limestone along with the fuel.

Bench-scale testing with the DSAF showed that a new sintered chrome–alumina refractory brick material prepared by Kyocera is at least 70% more resistant to flowing slag corrosion than the fusion-cast alumina material currently in use in the RAH. Other DSAF tests show that prefiring an experimental 98% alumina castable refractory to 2957°F (1625°C) reduces the corrosion rates by 75% compared to material prefired to only 2732°F (1500°C). Coatings used to seal the pores of the refractory were ineffective at reducing corrosion rates by Illinois No. 6 slag, but may be effective for more basic slags.

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GLOSSARY OF TERMS AND DEFINITIONS

acfm	actual cubic feet per minute
ACI	American Concrete Institute
AES	Auger electron spectroscopy
Al ₂ O ₃	alumina (aluminum oxide)
ASTM	American Society for Testing and Materials
Btu	British thermal unit
°C	degrees Celsius
CAH	convective air heater
CaO	calcium oxide
CCSEM	computer-controlled scanning electron microscopy
CDF	controlled density fill
CLSM	controlled low-strength materials
cm	centimeter
CO	carbon monoxide
CO ₂	carbon dioxide
DOE	Department of Energy
DOT	Department of Transportation
DSAF	dynamic slag application furnace
EERC	Energy & Environmental Research Center
°F	degrees Fahrenheit
FD	forced draft
Fe ₂ O ₃	iron(III) oxide
FGD	flue gas desulfurization
FGR	flue gas recirculation
ft	feet
ft/s	feet per second
HAT	humid air turbine
HHV	higher heating value
HiPPS	high-performance power system
HITAF	high-temperature advanced furnace
hr	hour
i.d.	inside diameter
ID	induced draft
IFRF	International Flame Research Foundation
in.	inch
K	Btu-in./ft ² F-hr
K ₂ O	potassium oxide
kg	kilogram
kJ	kilojoule
LRAH	large radiant air heater
lb	pound
LEBS	low-emission boiler systems

m	meter
m ²	square meter
m ³	cubic meter
M-26A	EPA Method 26A
EPA M-29	EPA Method 29
MA 754	high-temperature alloy
MgO	magnesium oxide
min	minute
MMBtu	million (10 ⁶) British thermal units
mmHg	millimeters of mercury
MOR	modulus of rupture
Na ₂ O	sodium oxide
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
NO _x	nitrogen oxides (nitric oxide and nitrogen dioxide)
NSPS	New Source Performance Standards
o.d.	outside diameter
O ₂	oxygen
pc	pulverized coal
PCA	primary combustion air
PFBC	pressurized fluidized-bed combustion
P ₂ O ₅	phosphorus pentoxide
PP	pressed powder
ppm	parts per million
psi	pounds per square inch
PSI	Physical Sciences, Inc.
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PTFE	polytetrafluoroethylene
RAH	radiant air heater
s	second
SCA	secondary combustion air
scfm	standard cubic feet per minute
SEM	scanning electron microscopy
SFS	slagging furnace system
SiO ₂	silica (silicon dioxide)
SRAH	small radiant air heater
SO ₂	sulfur dioxide
SO ₃	sulfur trioxide
SOAPP	State-of-the-Art Performance Program
std. dev.	standard deviation
SRM	standard reference material
t-fired	tangentially fired
TiO ₂	titanium oxide
UTRC	United Technologies Research Center

wt%	weight percent
W.C.	water column
WDS	wavelength-dispersive spectrometry
WDXRF	x-ray fluorescence wavelength
XRD	x-ray diffraction
XRF	x-ray fluorescence

TASK 3.3 – HIGH-TEMPERATURE HEAT EXCHANGER TESTING IN A PILOT-SCALE SLAGGING FURNACE SYSTEM

EXECUTIVE SUMMARY

1.0 EXPERIMENTAL APPROACH

The objective of the completed work was to improve the performance of a high-temperature heat exchanger, as well as to develop methods for reducing corrosion of brick and castable refractory in slagging coal-fired combustion systems. Specific technical issues of interest included measuring the effects of coatings on heat transfer in a radiant air heater (RAH) heat exchanger panel, demonstrating the fuel flexibility of the combustor concept, and developing ways to treat brick and castable refractories to increase their resistance to slag corrosion. Some limited sampling during slagging furnace system (SFS) operation was completed to characterize flue gas emissions (sulfur dioxide, nitrogen species, and particulate); evaluate pulse-jet baghouse performance; and document fuel, slag, and ash properties.

The scope of work consisted of two tasks. Task 1 involved the completion of three test periods and nearly 4 weeks of pilot-scale SFS operation. The first 2 weeks were nonconsecutive, with the third and fourth weeks representing continuous SFS operation. Each test period consisted of nominally 24 hours of natural gas firing to preheat the furnace and 38 to 150 hours of coal firing at a single operating condition. Two of the nearly 4 weeks of SFS operation involved firing a low-iron eastern Kentucky bituminous coal to determine if slag tapping presented special problems with such a coal as well as its slag corrosion characteristics relative to the ceramic tiles on the RAH panel. Other test parameters included operating the RAH panel at higher (>1700°F/>927°C) process air outlet temperatures, the use of noncoated refractory brick tiles on the surface of the RAH to determine the effect of previous high-emissivity coatings on heat exchanger efficiency, and the use of coal additives to mitigate slag flow problems and/or reduce slag corrosion of the refractories. Performance of the convective air heater (CAH) tube bank was evaluated relative to heat transfer from the flue gas to a hot airstream and the impact of ash deposition on the alloy tube surfaces.

In addition to the pilot-scale tests, bench-scale tests (Task 2) of methods to increase the corrosion resistance of refractories and reduce the corrosiveness of coal slag were completed. One hundred-hour flowing slag corrosion tests were performed, with slag collected from the SFS, on a chromia–alumina brick refractory in the dynamic slag application furnace (DSAF). The refractory recession was measured as well as the depth of penetration into the refractory by cross-sectioning the blocks and analyzing them in a scanning electron microscope (SEM). These tests were complemented with determinations of appropriate coal additives that could be used to decrease the slag corrosion rates either by increasing the slag viscosity (but still keeping it flowable), or by actually freezing a thin layer of slag on the surface of the refractory. This was done by measuring the viscosity versus temperature curves for the slag plus additives including aluminum oxide, silicon dioxide, and calcium oxide to determine their relative effects on the slag viscosity versus temperature.

2.0 RESULTS AND OBSERVATIONS

2.1 SFS Operation

The pilot-scale SFS was fired on Illinois No. 6 coal during the period January 24–29, 1999, on an eastern Kentucky bituminous coal during the period February 14–19, and on an eastern Kentucky coal and Illinois No. 6 coal during the period April 4–16. The purpose of the January test was to evaluate the RAH panel following its reassembly and installation, test a new high-density inner-layer refractory design while firing coal, and test two refractory coatings painted on small areas of the high-density inner refractory layer to determine if they would help reduce slag corrosion of the refractory. The purposes of the February and April tests were to continue the evaluation of the RAH panel, demonstrate furnace performance with a low-iron high-ash-fusion-temperature coal, and increase the number of hours of RAH exposure to slagging furnace conditions. The Kentucky coal used in February and April tests was selected because of its significant commercial interest and because it presented significantly different ash/slag properties compared to the Illinois No. 6 coal.

A comparison of the two bituminous coals fired in the SFS shows that the Illinois No. 6 coal contained twice the moisture (4.4–5.1 wt% versus 2.3–2.5 wt%), four times the sulfur (3.6–3.7 wt% versus 0.8–1.0 wt%), and nearly three times the ash (11.2–11.3 wt% versus 3.9–4.7 wt%). As a result of these fuel characteristics, the heating value of the Kentucky coal was 21%–26% greater than that of the Illinois No. 6 coal, 13,861–14,120 Btu/lb (32,210–32,812 kJ/kg) versus 11,257–11,328 Btu/lb (26,159–26,324 kJ/kg) on an as-fired basis. Coal ash analyses determined that the Kentucky coal ash contained significantly less silica, more alumina, and somewhat less iron and calcium. These differences in ash chemistry resulted in ash fusion temperatures that were significantly higher (100° to 200°F/56° to 111°C) for the Kentucky coal ash.

During the 4 weeks of SFS operation, the total furnace firing rate (main plus auxiliary burners) ranged from 2.7 to 3.0 MMBtu/hr (2.8 to 3.1×10^6 kJ/hr). The main burner firing rate ranged from 2.1 to 2.27 MMBtu/hr (2.2 to 2.3×10^6 kJ/hr), accounting for 73% to 82% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2740° to 2840°F (1505° to 1560°C). Operating problems encountered during the January and February tests were related to slag screen performance, specifically plugging/differential pressure control. No operating problems were encountered during the April test as a result of mitigating steps taken to avoid the slag screen performance problems previously encountered. The slag tap never plugged during the 4 weeks of operation.

Inspection of the furnace refractory after the January, February, and April tests indicated that the new high-density refractory was in excellent condition. The only area showing any deterioration was below the RAH panel where slag from the panel was dripping onto the high-density refractory below. In addition, the approach used to install the new high-density refractory prior to the January test eliminated the cracking observed immediately after the original high-density refractory was cured in 1997. The only observed change in the high-density liner as a function of operation is that the color appears to get a little darker with each test, indicating slag

penetration into the refractory. This change in appearance may indicate the potential for a failure of the high-density furnace liner if the refractory chemistry is sufficiently modified. Therefore, further work is definitely needed relative to the selection and performance of refractory materials to be used in commercial high-temperature furnace applications.

Two coatings were applied to specific areas of the high-density refractory surface to improve its slag corrosion resistance prior to the January test. The coatings were chosen on the basis of their performance in laboratory tests. After the SFS test, the coatings were no longer visible. Apparently the coatings were eroded from, or absorbed into, the surface of the high-density refractory. On the basis of the pilot-scale observations, further bench-scale development work is necessary before additional coating tests will be performed in the pilot-scale slagging furnace.

Because of the slag screen plugging problem observed in February and the large amount of residual slag left in the slag screen following the February test, the EERC elected to rebuild the slag screen prior to the April test. In order to improve the performance of the slag screen when the Kentucky bituminous coal was fired, only three rows of tubes were installed (1, 3, and 5). Eliminating three rows of tubes was meant to accomplish three objectives: 1) reduce the heat loss in the slag screen, 2) reduce the collection efficiency of the slag screen, and 3) lessen the drag on the flow of the slag out of the screen. Reducing the heat loss in the slag screen was expected to result in a higher slag temperature and a lower slag viscosity, improving slag flow from the slag screen to the slag tap. Reducing the collection efficiency of the slag screen would permit smaller alumina- and silica-rich clay-derived slag particles to escape to the dilution/quench zone and CAH section of the SFS.

Because of the high ash fusion temperature of the eastern Kentucky coal ash, slag screen differential pressure began to increase as soon as coal firing began in April. In order to modify the slag chemistry and reduce its ash fusion temperature, control slag screen differential pressure, and avoid plugging problems, a feed system was set up to add -40-mesh (-370- μ m) limestone to the coal at the point it entered the primary airstream. The effectiveness of the limestone addition was evaluated for limestone feed rates ranging from 0.25 to 2 lb/hr (113 to 908 g/hr). Ultimately, slag screen differential pressure was stabilized and effectively controlled at 0.5 in. W.C. (0.12 kPa) using a limestone feed rate of 0.5 lb/hr (227 g/hr). The 0.5 lb/hr (227 g/hr) limestone feed rate increased the total solids rate into the slagging furnace by nominally 0.3 wt%. The corresponding increase in the ash rate into the slagging furnace was nominally 3.7 wt%, based on the calcium oxide addition to the ash.

Baghouse temperature ranged from 330° to 367°F (166° to 186°C) during the 4 weeks of operation. Flue gas flow rates were 884 to 1046 scfm (25.0 to 29.6 m³/min), while actual flue gas flow rates through the baghouse were 1401 to 1692 acfm (39.7 to 47.9 m³/min). The 36 bags (total filtration area of 565 ft² [52.5 m²]) used in the baghouse were a 22-oz/yd² (747 g/m²) woven glass with a PTFE (polytetrafluoroethylene) membrane. The filter face velocities ranged from 2.4 to 3.0 ft/min (0.74 to 0.91 m/min). These filter face velocities are low compared to conventional pulse-jet filtration systems typically operating at or near 4 ft/min (1.2 m/min). Particulate emissions from the pulse-jet baghouse were as low as 0.0014 lb/MMBtu while

effectively using on-line cleaning and a reservoir pulse-air pressure of nominally 40 psig (2.8 bar) to control differential pressure in the range of <2 to 6 in. W.C. (<4 to 11 mmHg). Cleaning frequency ranged from 3 to 8 hours, depending on the fuel type and limestone (for modifying slag chemistry) or calcium oxide (for controlling flue gas sulfur trioxide concentrations) addition.

2.2 CAH Performance

The CAH tube bank was installed and initially evaluated during a shakedown test completed in October 1997. Through April 1999, the CAH tube bank has experienced twelve heatup/cooldown cycles as a result of 1716 hours of coal/lignite (731 hours) and natural gas (985 hours representing SFS heatup/cooldown and refractory curing) firing in the SFS. Based on a single thermocouple measurement, the clean tube surface temperatures were nominally 1565°F (852°C), with the surface temperature decreasing to 1340°F (982°C) as ash deposits developed and adjustments were made to the process air flow rate during the tests. When coal firing (Illinois No. 6 or eastern Kentucky) began, surface temperatures initially decreased at a rate of nominally 5°F/hr (3°C/hr) for 10 (eastern Kentucky) to 20 hours (Illinois No. 6). After nearly 40 hours of coal firing, there was no further decrease in tube surface temperature for either fuel. As ash deposits developed on the tube surfaces when the Illinois No. 6 and eastern Kentucky coals were fired, heat recovery from the CAH tube bank decreased 60% and 40%, respectively. The CAH ash deposition rate while the Illinois No. 6 coal was fired was 0.03 lb/MMBtu (13.3 g/10⁶ kJ), compared to 0.01 lb/MMBtu (5.9 g/10⁶ kJ) for the eastern Kentucky coal. Overall, these results are due to the smaller quantity of ash in the Kentucky fuel as well as the differences in ash properties. However, these data do not address the potential for improved heat recovery for either fuel type as a function of an effective sootblowing system.

CAH tube bank plugging was not a problem during the SFS tests. No deposits were observed bridging the flue gas paths between the tubes. The deposits that formed were limited to the leading and trailing edges of the tubes. However, when the Illinois No. 6 coal was fired, deposits did bridge the area between the tubes in the direction of the flue gas flow. Deposit strength is a function of ash chemistry, particle size, and temperature history. The relative strength of the Illinois No. 6 deposits was indicated by the fact that the deposits generally remained intact when the CAH tube bank was removed from the duct. Also, the deposits were generally removed intact from the tube surfaces. In contrast, following the eastern Kentucky coal test, the ash deposits from the cooled tubes were not generally removed intact from the tube surfaces.

Characterization of the eastern Kentucky ash deposits shows that the deposits are dominated by larger particles enriched in silica (about 50% silica) and iron, and depleted in alumina and calcia. Because all alkali and alkaline-earth species were present in very low concentrations, limited deposit sintering at the temperatures of the CAH was observed. It is unusual that the compositions of the upstream and downstream deposits are so similar, since the upstream deposits are usually more enriched with larger particles and the downstream deposits usually more enriched with smaller particles. SEM analyses showed that essentially all of the deposits were composed of complex silicates, except for a thin powder layer adjacent to the tube, which contained approximately 15% sulfate material.

On the basis of CAH data developed during this test series, it appears that the addition of the fins to the air-cooled tubes improved heat recovery during the coal-fired test periods. The fins appear to have reduced the rate of heat-transfer degradation as ash deposits developed and helped to maintain a higher heat-transfer rate once the deposits had formed. However, no improvement in heat recovery was observed during the initial natural gas-fired periods with clean tube surfaces.

2.3 RAH Performance

Initial shakedown and testing of the RAH panel took place in December 1997. Testing of the RAH panel continued in January, February, and April 1999 following its reassembly in early January. Reassembly of the RAH panel was necessary because of ceramic tile failures in August 1998. Through April 1999, the RAH panel experienced ten heatup/cooldown cycles as a result of 1485 hours of coal/lignite (684 hours) and natural gas (801 hours representing SFS heatup/cooldown and refractory curing) firing in the SFS. The new ceramic tiles that were installed in January 1999 were exposed to three heating and cooling cycles and 480 hours of slagging furnace operation: 181 hours of natural gas firing (including heatup and cooldown) and 299 hours of coal firing. The longest continuous coal-fired period was 184 hours. The primary purpose of the SFS tests summarized in this report was to further evaluate the RAH panel performance relative to heat transfer, tile and tube temperatures, and process air temperatures and flow rates. In addition, a critical aspect of RAH panel performance is the ability of the ceramic tiles to withstand the slag attack and thermal cycling conditions in the slagging furnace. Generally, the performance of the RAH panel during the three test periods was as anticipated, with no significant process or material problems observed.

The new RAH ceramic tiles were thoroughly inspected upon initial installation and following each week of operation. Initial inspection revealed the presence of minor cracks in two of the five ceramic tiles. These cracks were hairline cracks in the large upper and lower tiles. In addition, rough surface pitting was evident in the center of the large upper tile. The cracks found in new tiles are believed to result from stresses encountered during tile fabrication—the actual casting/cooling process, as well as the machining of the tiles. These stresses and the resulting cracks could be reduced if the tiles could be formed in near-net shapes, eliminating the need for machining. Work in this area is progressing within the Combustion 2000 HiPPS (high-performance power system) program.

Exposure of the RAH ceramic tiles to slag during coal firing in January darkened the tiles as a result of the residual slag layer on the surface. No additional tile color change was evident following the subsequent tests. The slag layer on the tiles is thin and appears to be uniform, with no evidence of any extensive slag buildup. While there was some slag present in the seams between the tiles, there was no evidence of any fusion between adjacent tiles. Therefore, the 4-hour period of natural gas firing prior to SFS cooldown appears to be adequate to prevent buildup of excess slag on the surface of the tiles or in the seams between tiles for the Illinois No. 6 and Kentucky bituminous coals. Also, any quantity of slag present in the seams between tiles appears to crack as a result of cooldown and tile movement.

Following the April test, cracks were evident in four of the five tiles. In general none of the cracks indicates the potential for a near-term tile failure. However, the combination of cracks in the small and larger upper tiles could be problematic with further heating and cooling cycles. Heatup/cooldown cycles are believed to contribute significantly to the RAH panel ceramic tile/brick cracking and the propagation of cracks formed during tile fabrication, with slag contributing to erosion/corrosion of surfaces and imparting stresses on the ceramic tile as it finds its way into seams between tiles. This observation is consistent with those made concerning the original RAH tiles installed in December 1997 and removed subsequent to failure in August 1998.

Overall, the condition of the ceramic tiles deteriorated somewhat with each test, with the small lower tile showing the greatest degree of erosion/corrosion. This is believed to result from the combination of its higher surface temperature and the greater quantity of slag flowing over its surface relative to the other tiles. The surface temperature of the small lower tile, although not measured, is believed to be higher than that of the three larger tiles because the backside of this tile is insulated within the radiation cavity and is not directly cooled by the heat-transfer surfaces. The greatest quantity of slag also flows over this tile because of its location below the other tiles.

RAH process air flow rates were typically controlled at 180 and 200 scfm (5.1 and 5.7 m³/min). As a result, cavity-side ceramic tile surface temperatures ranged from nominally 2000° to 2205°F (1094° to 1208°C), while higher tile surface temperatures, 2620° to 2693°F (1438° to 1479°C), were measured on the furnace side.

RAH tube surface temperatures ranged from nominally 1330° to 1980°F (721° to 1083°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Process air inlet temperature ranged from 1130° to 1195°F (610° to 646°C) but was nominally 1160° to 1190°F (627° to 644°C) for the coal-fired operational periods. Outlet process air temperatures ranged from nominally 1610° to 1900°F (877° to 1038°C). RAH temperatures are dependent on process air flow rate, process air inlet temperature, and furnace firing conditions.

At process air flow rates of 180 and 200 scfm (5.1 and 5.7 m³/min), the heat recovered from the RAH panel during coal firing was generally >126,000 Btu/hr (>132,930 kJ/hr) in January. This was a significant improvement in heat recovery rate compared to previous tests firing the same Illinois No. 6 coal, where the heat recovery rate in the RAH panel was <120,000 Btu/hr (<126,600 kJ/hr). In February, when the eastern Kentucky coal was fired at comparable operating conditions, the heat recovered from the RAH panel was >131,700 Btu/hr (>138,944 kJ/hr). However, in April, the RAH heat recovery was significantly lower: 115,385 to 125,000 Btu/hr (121,731 to 131,875 kJ/hr).

The highest RAH heat recovery rate was observed in February 1999 (eastern Kentucky coal), with fuel quality believed to be the reason for the lower heat recovery rate in January (Illinois No. 6 coal). A comparison of the eastern Kentucky coal-fired tests in February and April shows a decrease in the RAH panel heat recovery rate for April. Overall, the data indicate that the heat recovery rate for the RAH panel is decreasing with each week of operation since the slagging

furnace high-density refractory was replaced in late 1998 and the RAH panel was reassembled in January 1999. A comparison with prior and subsequent data also supports this conclusion.

EERC personnel believe that one or two possible factors are causing this change in RAH panel performance relative to heat transfer from the furnace to the radiation cavity. One possibility is a potential change to the RAH ceramic tiles resulting in a decrease in the heat transfer to the radiation cavity. The flame-side surface of the RAH ceramic tiles did darken as a result of slag coating and absorption during the January 1999 test. However, it is not clear what the effect would be on radiant heat absorption or emission or thermal conductivity. Also, no additional color changes were noted following subsequent test periods. In addition, erosion/corrosion of the ceramic tiles may be affecting their heat-transfer properties.

Another potential contributing factor to the decreasing heat transfer may be the high-density furnace refractory color change observed with each week of operation. As the high-density refractory has darkened with each week of operation, it is possible that the reflectivity, emissivity, or conductivity characteristics of the furnace liner have changed, resulting in a decrease in radiation to the RAH panel. Further testing will be necessary to determine if the observed decrease in RAH panel heat recovery rate continues with subsequent test periods or if an alternate explanation can be identified.

Based on the RAH heat-transfer data obtained during the three test periods completed, no conclusion can be drawn concerning the use or nonuse of a coating on the cavity side of the RAH ceramic tiles to improve cavity-side heat transfer.

2.4 Bench and Laboratory Corrosion Testing

Bench-scale testing with the DSAF showed that a new sintered chrome–alumina refractory brick material prepared by Kyocera is at least 70% more resistant to flowing slag corrosion than the fusion-cast alumina material currently in use in the RAH. In addition, the corrosion channel was much narrower than for the fusion-cast material, so actual service lifetime may be substantially better than indicated by the 70% reduction figure. Also, toxicity characteristic leaching procedure (TCLP) tests showed that the slag flowing over the Kyocera material does not absorb enough chromia to become a disposal problem. Other DSAF tests show that prefiring an experimental 98% alumina castable refractory to 2957°F (1625°C) reduces the corrosion rates by 75% as compared to material prefired to only 2732°F (1500°C). Coatings used to seal the pores of the refractory were ineffective at reducing corrosion rates by Illinois No. 6 slag, but may be effective for more basic slags.

Slag viscosity testing showed that there can be considerable variation in the temperature below which the slag does not flow well for basic slags, which tend to freeze rapidly. However, adding 10% calcia to a high-calcium Rochelle slag substantially reduced the freezing temperature of the slag. Alumina and silica additions had little effect. Additions of calcia, alumina, or silica to a lignite slag had little effect on the flow properties of a lignite slag, although the alumina addition may increase its propensity to freeze quickly upon cooling. However, the freezing temperature is

still too low to make a 10% addition effective in causing the slag to freeze on the refractory in a combustor system, thereby increasing the corrosion resistance of the refractory.

3.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A number of accomplishments have been achieved as a result of the bench- and pilot-scale work summarized in this report, as well as the work completed to date in support of the Combustion 2000 Program. On the basis of results and observations from both activities, the EERC believes that further development and evaluation of the high-temperature heat exchangers and materials related to their successful use is warranted. Specific activities to be considered are summarized in the following paragraphs.

New high-density castable refractory and castable ceramic formulations were developed in cooperation with commercial vendors. These new materials are more resistant to the erosive/corrosive properties of slag than those initially evaluated. In addition, higher curing temperatures were successfully applied to high-density castable refractories, resulting in improved resistance to slag erosion/corrosion. However, further development of these materials for use in high-temperature furnace applications with emphasis on their resistance to slag erosion/corrosion is necessary before commercial application will be possible.

Partial success was achieved with respect to casting ceramic tiles in near net shapes, limiting the need for machining and thus reducing stress cracking. However, further development of ceramic component fabrication methodology with an emphasis on casting near net shapes to eliminate machining requirements is necessary to eliminate RAH tile stress cracking and reduce the cost of RAH ceramic tiles.

Bench-scale tests successfully demonstrated the use of additives to modify slag properties. Specifically, additives were successfully used to increase and decrease slag viscosity for acidic and basic slags. Bench-scale tests with an alumina additive were successful in reducing refractory corrosion. During pilot-scale tests, limestone added to the pulverized fuel was successfully used to prevent slag screen plugging and control differential pressure. On the basis of these observations, further development of coatings that can be applied to refractory or ceramic surfaces to effect the desired changes in heat transfer or improve the resistance of these materials to slag erosion/corrosion is warranted.

Bench-scale tests have been used to identify a high-temperature window in which the products of coal combustion are much less corrosive toward the alloy MA-754 used to fabricate tubes for the RAH panel. This information indicates it would be appropriate to determine the potential to operate the RAH panel without fireside ceramic tile protection at furnace exit temperatures comparable to those found in conventional pulverized coal (pc)-fired boilers. This information would be very valuable in determining the potential application of the MA-754 alloy to repowering projects.

The pilot-scale SFS has been successfully operated in support of the high-temperature heat exchanger development effort firing lignite, subbituminous coal, or bituminous coal. CAH tube bank performance has been problem-free when these fuel types are fired, resulting in process air temperatures of nominally 1300°F (705°C). Successful operation of the RAH panel when the same fuels are fired has also been demonstrated, resulting in process air temperatures of 1700° to 2000°F (927° to 1094°C). Therefore, further development and testing of the high-temperature heat exchanger is warranted. Specific activities should address 1) investigation of alternative alloy and ceramic materials that will permit operation of the RAH panel at temperatures higher than those observed to date for process air temperatures of >2000°F (>1094°C), 2) corrosion testing of alloy materials for fireside applications, 3) integrated operation of the CAH tube bank and RAH panel with a turbine, 4) integrated operation of the CAH tube bank and RAH panel with a fuel cell, and 5) cofiring biomass in the high-temperature SFS and documenting overall system performance as well as specific efficiency losses that may occur relative to the performance of the CAH tube bank and the RAH panel.

On the basis of work completed to date, the high-temperature advanced furnace (HITAF) concept appears to offer a higher-efficiency technology option for coal-fired power generation systems than conventional pc firing. Concept analyses have demonstrated the ability to achieve program objectives for emissions (10% of New Source Performance Standards, i.e., 0.003 lb/MMBtu of particulate), efficiency (47%–55%), and cost of electricity (10%–25% below today's cost). Higher-efficiency technology options for new plants as well as repowering are important to the power generation industry in order to conserve valuable fossil fuel resources, reduce the quantity of pollutants (air and water) and solid wastes generated per MW, and reduce the cost of power production in a deregulated industry.

Possibly more important than their potential application in a new high-temperature power system, the RAH panel and CAH tube bank are potential retrofit technology options for existing coal-fired boilers to improve plant efficiencies. Therefore, further development of these process air-based high-temperature heat exchangers and their potential for commercial application is directly applicable to the development of enabling technologies in support of the Vision 21 program objectives.

TASK 3.3 – HIGH-TEMPERATURE HEAT EXCHANGER TESTING IN A PILOT-SCALE SLAGGING FURNACE SYSTEM

1.0 INTRODUCTION

The U.S. Department of Energy (DOE) projects that from 1995 to 2015, worldwide use of electricity will double to approach 20 trillion kilowatt hours. This growth comes during a time of concern over global warming, thought by many policy makers to be caused primarily by increases in carbon dioxide (CO₂) emissions through the use of fossil fuels. Government regulations now being negotiated in global treaties may force electric utilities to reduce CO₂ emissions or be forced to buy CO₂ credits from nations producing less CO₂ per capita. Unless coal-fired power plants are made more efficient, utilities may be forced to turn to more expensive fuels to avoid buying the credits.

One way to improve the efficiency of a coal-fired power plant is to use a combined cycle involving a typical steam cycle along with an indirectly fired turbine cycle using very high-temperature but low-pressure air as the working fluid. At the heart of an indirectly fired turbine combined-cycle power system are the very high-temperature heat exchangers that can produce clean air at up to 2600°F (1427°C) and 250 psi (17 bar) to turn an aeroderivative turbine. The overall system design can be very similar to that of a typical pulverized coal (pc)-fired boiler system, except that ceramics and alloys are used to carry the very high-temperature air. This design makes it especially suitable as a boiler repowering technology. With the use of a gas-fired duct heater, efficiencies of 55% can be achieved, leading to reductions in CO₂ emissions of 40%, as compared to today's coal-fired systems.

To support the development of this type of power system, the University of North Dakota Energy & Environmental Research Center (EERC) has designed, constructed, and operated a 3.0-million-Btu/hr (3.2×10^6 kJ/hr) slagging furnace system (SFS). Operational experience has shown that the SFS works very well and is well suited for testing very high-temperature heat exchanger concepts. Test results have shown that a high-temperature radiant air heater (RAH) panel designed and constructed by the United Technologies Research Center (UTRC) and used in the SFS can withstand temperatures of over 2000°F (1094°C). To support the pilot-scale work, the EERC has also developed laboratory- and bench-scale equipment to determine the corrosion resistance of possible refractory and structural materials and develop methods to improve corrosion resistance.

To expand this development effort, the EERC requested funding from the National Energy Technology Laboratory (NETL) in the amount of \$400,000 to perform approximately 3 weeks of tests in the EERC pilot-scale SFS to determine the effects of heat exchanger design, coal type, and coal additives on heat exchanger efficiency and material lifetimes in a slagging coal-fired environment. In addition, the EERC used laboratory- and bench-scale methods to test new refractories and ways to increase their corrosion resistance.

Increasing heat exchanger efficiencies and material lifetimes demonstrates to coal-burning utilities that coal-fired options exist and it may not be necessary to switch to natural gas firing or purchase CO₂ credits if CO₂ emission restrictions are legislated. Instead, existing coal-burning boilers can be repowered with an indirectly fired turbine combined cycle to increase efficiency by up to 50% and reduce CO₂ emissions by as much as 40%.

The results of each of the experimental tasks were documented in quarterly technical progress reports. These reports were sent to the NETL program monitor, and results were also included in reports to UTRC for inclusion in its quarterly reports to NETL under the Combustion 2000 high-performance power system (HiPPS) program. This document represents the final task report and contains a brief discussion of the scope of work, a description of the experimental systems, and documents operating conditions, the performance of the convective air heater (CAH) tube bank and RAH panel, flue gas emissions, and observations specific to the pilot- and bench-scale tests. Data are presented in tabular and/or graphical formats, conclusions based on the data are summarized, and recommendations for further work are offered, where warranted.

2.0 EXPERIMENTAL APPROACH

The objective of the proposed work was to improve the performance of a high-temperature heat exchanger, as well as to develop methods for reducing corrosion of brick and castable refractory in slagging coal-fired combustion systems. Specific technical issues of interest included the effects of coatings on heat transfer in an RAH heat exchanger panel, the general impact of firing a lower-iron bituminous coal on the operation of the RAH panel and SFS, and the development of ways to treat brick and castable refractories to increase their resistance to slag corrosion. Some limited sampling during SFS operation was completed to characterize flue gas emissions (sulfur dioxide, nitrogen species, and particulate); evaluate pulse-jet baghouse performance; and document fuel, slag, and ash properties.

The scope of work consisted of two tasks. The primary task involved the operation of the SFS. A second support task used analytical, laboratory, and bench-scale equipment to support the primary task and to develop methods to prevent excessive corrosion of the heat exchanger components.

2.1 Scope of Work

2.1.1 Task 1 – Evaluation of Heat Exchanger Performance in the SFS

Task 1 involved the completion of three test periods and nearly 4 weeks of pilot-scale SFS operation. The first 2 weeks were nonconsecutive, with the third and fourth weeks representing continuous SFS operation. Each test period consisted of nominally 24 hours of natural gas firing to preheat the furnace and 38 to 150 hours of coal firing at a single operating condition.

Specific test parameters were chosen based on the results of previous tests. Two of the nearly 4 weeks of SFS operation involved firing a low-iron eastern Kentucky bituminous coal to

determine if slag tapping presented special problems with such a coal as well as its slag corrosion characteristics relative to the ceramic tiles on the RAH panel. Other test parameters included operating the RAH panel at higher ($>1700^{\circ}\text{F}/>927^{\circ}\text{C}$) process air outlet temperatures, the use of noncoated refractory brick tiles on the surface of the RAH to determine the effect of high-emissivity coatings on heat exchanger efficiency, and the use of coal additives to mitigate slag flow problems and/or reduce molten slag corrosion of the castable and brick refractories.

Slagging furnace operation was evaluated based on furnace temperature (flue gas and refractory) and pressure measurements and on-line flue gas instrumentation readings (oxygen, carbon monoxide, CO_2 , nitrogen species, and sulfur dioxide). A nominal coal firing rate of 2.5 MMBtu/hr (2.6×10^6 kJ/hr) at an air-to-fuel ratio of about 1.2 was anticipated to achieve furnace gas temperatures of 2800°F (1538°C) near the furnace wall. Fuel selection was based on availability and properties such as ash fusion temperature and composition.

Special emphasis was placed on the collection of data to document the performance of the RAH panel located in the furnace wall. Performance of the RAH panel was evaluated relative to radiant heat transfer from the furnace to a hot airstream and the impact of slag on the ceramic tiles protecting the high-temperature alloy heat-transfer surfaces. Temperature measurements were made at the surfaces of the ceramic tiles and alloy heat-transfer tubes as well as of the bulk inlet and outlet process air. Comparisons are made with similar data generated during previous and subsequent test periods firing similar coals. The effects of the eastern Kentucky bituminous coal slag and the use of coal additives on the corrosion and erosion of the castable and brick refractory were evaluated based on observations before and after each week of operation. Photographs were taken to document observations.

Furnace exit, slag tap, and slag screen operating temperatures were selected based on ash fusion data for the specific fuels fired. These system temperatures are generally controlled at 100° to 200°F (56° to 111°C) above the fluid temperature of the slag under oxidizing conditions. Although the design and operation of these components are specific to the scale and design of the pilot-scale SFS, evaluating their performance is important to determining the impact of fuel properties on the relative performance of the RAH panel. The required flue gas recirculation (FGR) rate in the dilution/quench zone depends on the slag screen exit temperature. The FGR rate was controlled to achieve a flue gas temperature of 1800°F (983°C) entering the CAH tube bank.

Performance of the CAH tube bank was evaluated relative to heat transfer from the flue gas to a hot airstream and the impact of ash deposition on the metal tube surfaces. Temperature measurements were made to document the surface temperatures of the metal heat-transfer surfaces as well as bulk inlet and outlet process air temperatures. Comparisons are made with similar data generated during other bituminous coal-fired tests.

Heat recovery from the CAH tube bank is integral to the preheating of process air for the RAH panel in the furnace. However, it was not necessary to remove ash deposits from the CAH tube surfaces in order to achieve the process air conditions required to effectively support the operation of the RAH panel. As a result, data concerning deposition rate on the CAH heat-

transfer surfaces were estimated based on the weight of deposits collected and the duration of coal firing.

Ash deposits collected during two of the four test periods were characterized to determine chemical composition and relative strength. Specific analyses included x-ray fluorescence (XRF), scanning electron microscopy (SEM) point count, and SEM morphology. Acquiring this information is important because the firing characteristics of the SFS concept represent a firing condition different from either pc or cyclone firing. Flame intensity and furnace temperature are greater than pc firing, yet less intense; air-to-fuel ratios are higher than with cyclone firing.

Flue gas composition (sulfur dioxide, nitrogen species, CO₂, carbon monoxide, oxygen, and particulate) was measured and is reported. Gas-phase constituents were monitored continuously using on-line instrumentation at the exit of the furnace and pulse-jet baghouse. Sulfur dioxide and nitrogen species data are reported on a lb/MMBtu and concentration basis. Particulate sampling was completed at the inlet and outlet of the baghouse during each week of SFS operation. Sampling at the inlet of the baghouse documented mass loading and particle-size distribution. Sampling at the outlet of the baghouse documented mass and fine particulate emissions. Particulate emissions are reported on a lb/MMBtu and mass per unit volume basis.

Composite samples of coal, slag, and baghouse ash were collected for routine analysis. One composite coal sample was analyzed for each week of operation. Analyses included ultimate, proximate, Btu, dry-sieve, ash fusion (oxidizing), XRF, computer-controlled scanning electron microscopy (CCSEM), and ash viscosity. Analysis of slag involved at least one composite sample for each week of operation and included ash fusion, ash viscosity, and XRF. One baghouse ash composite sample was characterized for each week of operation. Analyses included Malvern particle size, carbon/hydrogen/nitrogen, and XRF. Composite samples of ash from other locations in the system were collected. Analysis of these samples depended on system performance observations and data analysis.

2.1.2 Task 2 – Bench-Scale Testing of Methods to Reduce Slag Corrosion

In addition to the pilot-scale tests, bench-scale tests of methods to increase the corrosion resistance of refractories and reduce the corrosiveness of coal slag were performed with the dynamic slag application furnace (DSAF). One 100-hour flowing slag corrosion test was performed with slag collected from the SFS on a chromia–alumina brick refractory and on coated and uncoated Plibrico Plicast 98 (98% alumina) castable refractory. The slag feeder was calibrated to deliver 0.11 lb of slag through each feed injector entry port during a 1-hour time period. This is approximately the maximum flow experienced in the pilot-scale slagging combustor. The refractory recession was measured as well as the depth of penetration into the refractory by cross-sectioning the blocks and analyzing them in an SEM.

These tests were complemented with determinations of appropriate coal additives that could be used to decrease the slag corrosion rates either by increasing the slag viscosity (but still keeping it flowable), or by actually freezing a thin layer of slag on the surface of the refractory. This was done by measuring the viscosity versus temperature curves for the slag plus additives

including aluminum oxide, silicon dioxide, and calcium oxide to determine their relative effects on the slag viscosity versus temperature.

These same additives have been used in other EERC work under the Combustion 2000 Program to vary the slag viscosity versus temperature behavior of an Illinois No. 6 coal slag and a Powder River Basin coal (Rochelle mine) slag because they simulate the use of inexpensive, naturally occurring materials such as bauxite, sand, or limestone as coal additives. Ten percent of each of the three pure oxides were added to one slag produced in the SFS tests.

2.2 Description of Pilot-Scale SFS

The EERC pilot-scale SFS is designed to simulate the conditions in the commercial-scale UTRC HITAF (high-temperature advanced furnace) concept. The SFS is pictured in Figure 2-1, with a schematic of the system shown in Figure 2-2. The SFS is designed for a maximum furnace exit temperature of 2900°F (1593°C), but is typically run at 2750°F (1510°C) at the exit in order to maintain the desired slag flow while extending the furnace lifetime. It has a nominal firing rate of 2.5 MMBtu/hr (2.6×10^6 kJ/hr) and a range of 2.0 to 3.0 MMBtu/hr (2.1 to 3.1×10^6 kJ/hr) using a single burner. The design is based on a bituminous coal (Illinois No. 6) and a nominal furnace residence time of 3.5 s. Resulting flue gas flow rates range from approximately 425 to 640 scfm (12 to 18 m³/min), with a nominal value of 530 scfm (15 m³/min) based on 20% excess air. Firing subbituminous coal or lignite increases the flue gas volume, decreasing residence time to as low as 2.7 s. However, the high volatility of subbituminous coal or lignite results in high combustion efficiency (>99%). The EERC oriented the furnace vertically (downfired) and based the burner design on a swirl burner successfully used on two smaller EERC pilot-scale pc-fired units (0.6 MMBtu/hr [0.7×10^6 kJ/hr]). The furnace dimensions are 47 in. (119 cm) inside diameter (i.d.) by roughly 16 ft (4.9 m) in total length. It is lined with three layers of refractory totaling 12 in. (30.5 cm) 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 relative to other commercially available castable refractories.

A key design feature of the furnace is accessibility for installation and testing of one large radiant air heater (LRAH) panel and one small radiant air heater (SRAH) panel. The panels were designed for testing material lifetimes and heat exchange coefficients. The LRAH is 1.5 × 6.4 ft (0.46 × 1.96 m). This size was based on manufacturing constraints identified by UTRC, which designed and built the panels. The LRAH contains three vertically oriented tubes made of MA754, an oxide dispersion-strengthened nickel-based alloy. The tubes are protected from slag corrosion by fusion-cast alumina refractory tiles. Process air to be heated by the LRAH panel is provided by an existing EERC air compressor system. As it passes through the LRAH panel, the process air is heated from 1300°F (705°C) to as much as 1800°F (982°C). However, tests completed in August 1998 with an Illinois No. 6 coal showed that temperatures as high as 2000°F (1094°C) can be reached with the current design.

Figure 2-1. Photograph of the pilot-scale slagging furnace system.

The SRAH was constructed with a variety of refractory tiles and was designed only for testing material lifetimes. However, in August 1998, severe tile deterioration and failure resulted in a technical and economic decision to remove the SRAH from service and make exclusive use of the LRAH panel for heat-transfer studies as well as evaluation of component performance relative to material lifetimes. Therefore, the SRAH panel was not available for use during this project.

As the hot gases leave the combustion zone, they pass through a slag screen, which is designed to remove the entrained ash as a nonleachable slag and reduce deposition on the CAH tubes. Tests with the slag screen showed that its performance is fuel-dependent and that when firing Illinois No. 6 coal 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 (1010°C) in order to reduce the stickiness of the ash to minimize deposition on the CAH tubes. The quench zone is the only region in the furnace where hard slag/ash deposits form, but they are easily removed by knocking them into a hopper at the bottom of the zone. The gases then pass through the CAH tube bank which is used to heat process air from 1000° up to 1300°F (538° to 705°C) to support operation of the RAH. The hot combustion gases flow from the CAH tube bank through a series of heat exchangers and, finally, a baghouse on the way to the system stack.

2.2.1 Fuel Feed System

The SFS fuel feed system serves two primary functions, a natural gas-firing capability and a solid fuel-firing capability. The natural gas-firing capability supports preheating the SFS with the main burner as well as the operation of the auxiliary burner and the two-port slag tap burner. Natural gas is supplied to the SFS through a 2-in. (5-cm) supply line, meter, and regulator at a pressure of about 8 psig (0.6 bar). Natural gas is then supplied to the individual SFS burners from a 2-in. (5-cm) header. Each of the three burners has its own set of controls and flame safety system. The natural gas feed system is integrated into the overall process control and data acquisition system.

Solid fuel firing only supports the operation of the main burner. To date, solid fuel firing has included pulverized bituminous and subbituminous coal and lignite. However, the firing of alternative solid fuels in the future is anticipated. The three primary components of the solid fuel feed system consist of two storage hoppers, two surge hoppers, and a weigh feeder. Each storage hopper has a nominal pulverized fuel capacity of 2400 lb (1090 kg) depending on fuel density. For bituminous coal firing, it is necessary to change out storage hoppers every 12 to 15 hours, while a lignite requires a hopper to be changed out every 6 hours. Surge hopper capacity is nominally 500 lb (227 kg) each. Each surge hopper has the capacity to refill the weigh feeder hopper twice, allowing for adequate time to change out the storage hoppers. Each surge hopper has a level indicator integrated with the process control and data acquisition system, which then opens and closes a valve supplying pulverized fuel from the storage hopper in auto mode. Refilling of the surge hoppers can also be operated in a manual mode.

Specifications for the weigh feeder included the following:

- Pulverized fuel density (40 lb/ft³ or 641 kg/m³)
- Particle size (70% <0.0030 in. or 75 µm; 300-µm top size)
- Feed rate range (200–500 lb/hr or 91–227 kg/hr)
- Minimum hopper capacity (10 ft³ or 0.3 m³)
- Nonpulsing feed (twin screw)
- Gravimetric (loss-in-weight) and volumetric feed modes
- Minimum 20-bit resolution load cell (high-resolution digital)
- User-programmable microprocessor control

The weigh feeder in use at this time is a K-Tron solids feeder. Operation of the weigh feeder is integrated into the overall process control and data acquisition system. Two sets of feeder screws were acquired so that the feeder gear ratio can be adjusted to achieve a fivefold change in feed rate capacity. Solids from the weigh feeder are discharged from the screws into an air eductor. The fuel is then pneumatically conveyed to the main burner through the primary air line. Refilling of the feed hopper can be operated in a manual or automatic mode. To date, controlled feed rates have ranged from nominally 160 lb/hr (72.6 kg/hr) for a bituminous coal to 300 lb/hr (136 kg/hr) when a lignite was fired. However, based on operating experience, the weigh feeder should be capable of delivering 1500 lb/hr (681 kg/hr).

The main burner is natural gas- and pulverized fuel-capable. The basic design is an International Flame Research Foundation (IFRF)-type adjustable secondary air swirl generator which uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl. Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NO_x. Carbon efficiency has been >99% in the slagging furnace for all fuels fired to date. High carbon efficiencies can be obtained in the slagging furnace at relatively low swirl settings because of the high operating temperature. Combustion air flow rates through the main burner range from about 400 to 600 scfm (11 to 17 m³/min), depending on furnace firing rate and the fuel type (bituminous, subbituminous, or lignite) fired.

An auxiliary gas burner (850,000 Btu/hr or 896,750 kJ/hr) is located near the furnace exit in order to control furnace exit temperature, ensuring desired slag flow from the furnace and the slag screen. This auxiliary burner is used to compensate for heat losses through the furnace walls, sight ports, and RAH test panels. The use of the auxiliary gas burner is beneficial during start-up to reduce heatup time and to prevent the freezing of slag on the slag screen tubes when the switch is initially made to solid fuel firing.

Although it is not possible to eliminate solid fuel feed plugs or bridging in the feed hopper, it is desirable to minimize them for process stability and safety reasons. To mitigate this problem when it occurs, two nitrogen purge nozzles are located in the feed hopper just above the screws. The purge system includes a pressure regulator, an adjustable timer, and a solenoid valve. The pressure regulator permits adjustments to the purge pressure, the timer permits adjustments to pulse duration, and the solenoid valve permits operation of the purge mechanism from the control room.

In addition to the air purge system, a fuel feed system alarm informs the process engineer when the fuel hoppers are in a refill cycle and screw speed exceeds an upper feed rate limit. Also, when the screw speed exceeds the limit, the controller is programmed to switch from a gravimetric to a volumetric feed mode, minimizing the potential for excessive solid fuel feed rates.

2.2.2 *Slagging Furnace*

Table 2-1 summarizes volumetric flow rate and temperature data upon which the furnace design was based. The vertically oriented furnace shell was designed to include four distinct furnace sections. The top section of the furnace supports the main burner connection, while the upper-middle furnace section provides a location for installation of the RAH panels. The lower-middle furnace section supports the auxiliary gas burner; the bottom section of the furnace includes the furnace exit to the slag screen as well as the slag tap opening. Flue gas temperature measurements have been made using two Type S thermocouples protruding 1 in. (2.5 cm) into the furnace through the refractory wall and three optical pyrometers (flame temperature, flue gas temperature along the furnace wall near the RAH panel, and flue gas temperature at the furnace exit). Furnace temperature is also measured using thermocouples located at the interface between the high-density and intermediate refractory layers, as well as between the intermediate and insulating refractory layers. A pressure transmitter and gauges are used to monitor static pressures in order to monitor furnace performance. These data (temperatures and pressure) are automatically logged into the data acquisition system and recorded manually on data sheets on a periodic basis as backup.

The slag tap was intended to be as simple and functional as possible. To that end, the original design was a simple refractory-lined hole in the bottom of the furnace. The diameter of the slag tap was 6 in. (15 cm), with the potential to change the diameter by simply removing or repouring refractory. To minimize heat losses, slag is collected in an uncooled, dry container with refractory walls. As a result of operating experience during SFS shakedown and subsequent tests, the slag tap refractory is replaced periodically, and the diameter of the hole was reduced to nominally 4 in. (10.2 cm) with a well-defined drip edge. In addition, a two-port natural gas-fired tap hole burner was added early in 1998. Although some slag tap deposits do form, no severe slag tap plugging was encountered during the three tests completed in support of this project. When the slag tap has plugged in the past year, the plug was typically removed on-line after a switch was made to natural gas firing for a short period of time (2 hours) in the main burner.

TABLE 2-1

Theoretical Flow and Heat-Transfer Data for the Slagging Furnace System (Illinois No. 6 bituminous coal)

Furnace Firing Rate, kBtu/hr:	2000	2500	3000		2000	2500	3000
Furnace				Furnace Exit/Slag Screen			
Furnace i.d., in.	47	47	47	Total Flue Gas Flow, scfm	592	646	663
Furnace Length, ft	16	16	16	Total Flue Gas Flow, acfm	3598	3926	4029
Refract. 1 Thickness, in.	4	4	4	Furnace Exit Vel., ft/s	33.2	36.2	37.2
Refract. 2 Thickness, in.	4	4	4	Slag Screen Exit Gas Vel., ft/s	66.4	72.5	74.4
Refract. 3 Thickness, in.	3.25	3.25	3.25				
Furnace Weight, tons	14.4	14.4	14.4	Dilution Gas Requirements			
				Inlet Flue Gas Temp., °F	2520	2535	2540
Inlet Gas Temp., °F	2900	3000	3100	Gas Velocity In, ft/s	61.3	67.3	69.2
Avg. Gas Temp., °F	2800	2850	2900	Exit Gas Temp., °F	1855	1851	1850
Exit Gas Temp., °F	2700	2700	2700	Dilution Gas Temp., °F	300	300	300
Refract. 1 Surf. Temp., °F	2677	2728	2777	Dilution Gas Flow, scfm	248	280	289
Refract. 2 Surf. Temp., °F	2431	2477	2521	Total Flue Gas Flow, scfm	840	926	952
Refract. 3 Surf. Temp., °F	1751	1783	1815	Flue Gas Flow Rate out, acfm	3740	4115	4229
Furnace Skin Temp., °F	275	279	283	Gas Velocity out, ft/s	67.6	74.4	76.5
Coal Feed Rate, lb/hr	176	220	264	Dilution Gas Nozzles			
Airflow Rate, scfm	398	497	597	Nozzle Diameter, in.	1.25	1.25	1.25
Flue Gas Flow Rate, scfm	428	536	643	No. of Nozzles	8	8	8
Flue Gas Flow Rate, acfm	2683	3412	4155	Dilution Gas Flow, acfm	362	409	422
Furnace Gas Velocity, ft/s	3.7	4.7	5.7	Dilution Gas Velocity, ft/s	89	100	103
Flue Gas Residence Time, s	4.1	3.2	2.6				
				Convective Air Heater			
Auxiliary Burner Air, scfm	164	110	20	Gas Temp., °F	1800	1800	1800
Auxiliary Burner, kBtu/hr	890	560	110	Flue Gas Flow Rate, acfm	3651	4025	4138
Total Firing Rate, kBtu/hr	2890	3060	3110	Gas Velocity, ft/s	52.2	57.5	59.1
Wall Losses, kBtu/hr	194	202	209				
RAH Losses, kBtu/hr	190	190	190				

Assumption: Excess air is 20%.

The refractory walls in the slagging furnace consist of three castable refractory layers with a total thickness of 11.25 in. (28.58 cm). The three layers include 4 in. (10.2 cm) of high-density (14 Btu-in./ft²-°F-hr or 2.0 W/m-K) slag-resistant material, 4 in. (10.2 cm) of an intermediate refractory (4.0 Btu-in./ft²-°F-hr or 0.6 W/m-K), and 3.25 in. (8.3 cm) of a low-density insulating refractory (1.3 Btu-in./ft²-°F-hr or 0.2 W/m-K). Three refractory layers were selected as a cost-effective approach to reduce the overall size and weight of the system. Because of its greater structural strength and high corrosion resistance, Plibrico Plicast Cement-Free 98V KK alumina castable was originally used in the top three furnace sections, in the exit of the furnace, and in the top section of the dilution/quench zone. The Plicast Cement-Free 98V KK is 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. Plicast Cement-Free 99V KK was used in the bottom furnace section (except for the exit) because of its even greater potential resistance to slag attack. Repairs to the high-density refractory in the top section of the furnace and the upper-middle furnace section are required on a periodic basis.

Complete replacement of the high-density furnace refractory was anticipated in the original Combustion 2000 scope of work, although the lifetime of the material was uncertain because of the variable slag deposition that was anticipated. Most of the original high-density refractory lasted until after the August 1998 test period, after which the decision was made to replace it because of extensive cracking caused by differences in the expansion and contraction of the inner and middle liners during each heating and cooling cycle. Actual corrosion of the high-density liner was minimal, except for newer patches that were not completely sintered and for areas of flame impingement. The timing worked out well with the need to replace/reassemble ceramic components in the RAH panel. Table 2-2 summarizes properties for refractories used in the SFS.

Although the Narco Cast 60 refractory in the top section of the furnace appeared to be in good shape, refractory deterioration was evident as a result of 2 weeks of lignite firing. Therefore, it was replaced with a Plibrico Plicast Cement-Free 96V refractory. This material will be less prone to corrosion than the Narco Cast 60 refractory, yet stronger and less prone to shrinkage than the Plibrico Plicast Cement-Free 98V KK refractory originally used in this section of the furnace.

Because of its greater structural strength and high corrosion resistance, Plibrico Plicast Cement-Free 98V alumina castable was used to replace the high-density refractory in the two middle furnace sections. Based on vendor information and bench-scale data, Plicast Cement-Free 98V was expected to be less prone to shrinkage than the 98V KK and 99V KK materials originally used in these furnace sections while having comparable slag corrosion resistance. Before the high-density refractory was poured, the middle refractory layer was lined with plastic and alumina-fiber paper to prevent the newly poured layer from sticking to the middle layer upon firing. In addition, plastic dividers were added to separate the high-density refractory into approximately 2-ft by 2-ft (0.6-m by 0.6-m) sections that could move independently to reduce fracturing. Total high-density refractory replacement was not necessary in the bottom section of the furnace. However, some repairs were made using the Plibrico Plicast Cement-Free 98V material.

TABLE 2-2

Refractory Properties

Refractory:	Plicast Cement-Free 99V KK/99V ¹	Plicast Cement-Free 98V KK/98V ¹	Plicast Cement-Free 96V KK/96V ¹	Narco Cast 60	Plicast LWI-28	Plicast LWI-20	Harbison-Walker 26
Function	High density	High density	High density	High density	Insulating	Insulating	Insulating
Service Limit, °F	3400	3400	3300	3100	2800	2000	2600
Density, lb/ft ³	185	185	185	145	80	55	66
K, Btu-in./ft ² °F-hr @ 2000°F	14.5	14.5	14.0	6.5	4.0	NA ²	2.2
K, Btu-in./ft ² °F-hr @ 1500°F	14.7	14.7	14.2	6.0	3.0	1.7	1.9
K, Btu-in./ft ² °F-hr @ 1000°F	15.5	15.5	15.0	5.6	2.7	1.3	1.7
Hot MOR ³ @ 2500°F, psi	650	750	1400	NA	NA	NA	NA
Hot MOR @ 1500°F, psi	—	—	2000	1000	250	100	110
Cold Crush Strength @ 1500°F, psi	—	—	10000	NA	750	400	350
Typical Chemical Analysis, wt% (calcined)							
Al ₂ O ₃	99.6	98.6	95.5	62.2	54.2	39.6	53.8
SiO ₂	0.1	1.0	3.8	28.0	36.3	31.5	36.3
Fe ₂ O ₃	0.1	0.1	0.1	1.0	0.8	5.4	0.5
TiO ₂	0.0	0.0	0.0	1.7	0.5	1.5	0.6
CaO	0.1	0.1	0.1	2.8	5.7	19.5	7.2
MgO	0.0	0.0	0.0	0.1	0.2	0.8	0.2
Alkalies	0.2	0.2	0.2	0.2	1.5	1.4	1.4

¹ The “KK” designation indicates the presence of fibers that promote dewatering during curing.

² Not applicable.

³ Modulus of rupture.

The condition of the high-density refractory in the upper sections of the furnace appears to be excellent following the tests completed in January, February, and April. However, the high-density refractory layer is getting darker with each test as a result of slag penetration. This change in the high-density refractory is discussed further in conjunction with the RAH panel later in the report. The approach used for high-density refractory replacement resulted in a complete separation of the high-density and intermediate refractory surfaces. This separation appears to have limited cracking and other refractory damage resulting from differential thermal expansion during heating and cooling cycles. However, high-temperature furnace operation when the eastern Kentucky coal is fired has resulted in further deterioration of the original high-density refractory in the bottom section of the furnace. As a result, the EERC replaced this refractory with the Plibrico Plicast Cement-Free 98V material in July prior to test periods planned in support of the Combustion 2000 Program.

2.2.3 *Radiant Air Heater Panels*

A key design feature of the furnace is accessibility for installation and testing of one LRAH panel and one SRAH panel. The panels were designed for testing material lifetimes and heat exchange coefficients. The large panel contains three vertically oriented tubes made of MA 754, a nickel-based oxide dispersion-strengthened alloy. The tubes are protected from slag corrosion by fusion-cast alumina refractory plates. The furnace design will accept an LRAH panel with a maximum active size of 1.5×6.4 ft (0.46×1.96 m). This size, which was selected to minimize furnace heat losses, was based on panel-manufacturing constraints identified by UTRC. Flame impingement on the RAH panels is not necessarily a problem because of the fusion-cast alumina ceramic tiles protecting the heat-transfer surfaces. Process air for the LRAH panel is provided by an existing EERC air compressor system having a maximum delivery rate of 510 scfm ($14.4 \text{ m}^3/\text{min}$) and a maximum stable delivery pressure of 275 psig (19 bar). The LRAH panel process air is heated from 1300° to 1700°F (705° to 927°C) as it passes through the LRAH panel, although during one test period, adjustments were made to the furnace firing rate (Illinois No. 6 coal) and the process air flow rate and pressure to achieve a LRAH process air exit temperature of 2000°F (1094°C).

Backup process air is available from a smaller compressor at a maximum delivery rate of 300 scfm ($8.5 \text{ m}^3/\text{min}$) and pressure of <100 psig (<7 bar). 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. In the event of a failure of inlet process air piping, a backflow emergency piping system was installed so that overheating of the LRAH panel could be avoided. The LRAH test panel arrived at the EERC on September 15, 1997. Final assembly and installation of the LRAH panel into the furnace occurred in November 1997. As a result of the ceramic tile failure that occurred in August 1998, all of the LRAH ceramic tiles were replaced in January 1999 prior to beginning tests in support of this project.

Furnace design also permits the installation of a smaller sized 1.5×5.4 -ft (0.46×1.65 -m) SRAH panel. The purpose of the SRAH panel was to expose ceramic materials to slagging furnace conditions to evaluate their slag corrosion properties rather than generating heat-transfer data. The SRAH was constructed with a variety of refractory plates and was designed only for

testing material lifetimes. A primary difference between the LRAH and SRAH panels was that the SRAH panel was cooled with water rather than heated air. The SRAH panel was water-cooled using two sets of five vertically oriented 0.375-in. (0.952-cm) outside diameter (o.d.) stainless steel tubes. While the SRAH panel was 1 ft (0.3 m) shorter than the LRAH panel, both assemblies were the same width and use the same air-cooled frame support design. A central vertical ceramic rail was present in the SRAH panel, allowing the installation of either full-width (18-in./46-cm) or half-width panels inside the furnace. The SRAH panel ceramic tiles were damaged in August 1998. Based on technical and economic considerations, the SRAH panel was not rebuilt. Therefore, the SRAH panel was not available for use in support of this project.

2.2.4 *Slag Screen*

The slag screen design for the pilot-scale SFS is the result of a cooperative effort between the EERC, UTRC, and Physical Sciences, Inc. (PSI), personnel. The primary objective for the pilot-scale slag screen is to reduce the concentration of ash particles entering the CAH. Design criteria specific to the pilot-scale slag screen include 1) a simple design permitting modifications if necessary using readily available, inexpensive materials; 2) matching duct dimensions and flue gas flow rates to maintain turbulent flow conditions; 3) minimizing the potential for plugging as the result of slag deposit growth on tube surfaces or the sloped floor; 4) limiting differential pressure across the slag screen to 2-in. W.C. (4 mmHg); and 5) limiting heat losses to ensure desired slag flow from the slag screen to the furnace slag tap. The slag screen flue gas approach velocity is nominally 70 to 75 ft/s (21.4 to 22.9 m/s) depending on furnace firing rate and fuel type. The flue gas outlet temperature from the slag screen must be $>2500^{\circ}\text{F}$ ($>1371^{\circ}\text{C}$) to minimize the potential for slag freezing in the slag screen.

The slag screen typically makes use of six rows of three 1.5-in. (3.8-cm)-diameter vertical tubes mounted in an upwardly sloped duct (20 degrees) to facilitate slag flow from the slag screen into the furnace slag tap. The center line-to-center line tube spacing in each row is 3.75 in. (9.5 cm). Center line-to-center line spacing between individual rows is 4 in. (10.2 cm). Internal duct dimensions for the slag screen are 10 in. $\times$ 13 in. $\times$ 3.5 ft (25 cm $\times$ 33 cm $\times$ 1.1 m). The resulting flue gas velocity through the slag screen is roughly 91 ft/s (28 m/s).

Type S thermocouples (one each) in the vicinity of the first and last row of tubes are used to monitor slag screen temperature. Thermocouple data are automatically logged on the data acquisition system. Pressure taps were installed in the roof upstream and downstream of the tubes to monitor and record slag screen differential pressure. As a backup to the data acquisition system, slag screen data are recorded manually on data sheets on a periodic basis. Continuous flue gas sampling occurs between the slag screen and the dilution/quench zone to monitor and control slagging furnace operation.

The walls of the slag screen consist of two refractory layers. The inner, high-density layer is a Plicast Cement-Free 98V KK with an outer insulating layer of Harbison-Walker Castable 26. The high-density refractory is 2.25 in. (5.7 cm) thick in the sidewalls and 4 in. (10.2 cm) thick in the roof and floor of the slag screen. The insulating refractory is 3.75 in. (9.5 cm) thick in the sidewalls, roof, and floor. A Plicast LWI-28 refractory was used around the sight ports in the wall

of the slag screen. Properties for the high-density and insulating refractories selected for use in the slag screen are summarized in Table 2-2.

Slag screen tubes are fabricated using castable high-density refractory poured inside aluminum pipe. The aluminum pipe makes a structurally sound form during curing and eventually melts and runs into the slag pot as furnace temperatures rise. Water-cooled surfaces inside of the refractory tubes and the floor of the furnace exit/slag screen inlet are intended to cool the high-density refractory surface and reduce the erosion/corrosion originally observed during shakedown tests. Initial water-cooled surfaces installed inside of the 1.5-in (3.8-cm) high-density refractory tubes were 0.125-in. (0.32-cm) 316 SS tubing. However, subsequent operating experience with Illinois No. 6 bituminous coal showed that the front half of each tube in the first and second rows had been severely eroded/corroded. The remaining tubes all had a slag layer over the surface of the refractory. Based on these observations, the diameter of the water-cooled 316 SS tubing in the first and second rows was increased from 0.125 in. (0.32 cm) to 0.188 in. (0.476 cm). The larger diameter water-cooled tubing in the first and second rows of tubes further reduces the surface temperature of these tubes and the resulting erosion/corrosion observed.

Based on slag screen operating experience with bituminous coal, subbituminous coal, and lignite, EERC personnel have determined that the high-density refractory is an acceptable tube material and that the size of the water-cooled tubes inside of the high-density refractory must be changed depending on the type of fuel. During lignite-fired tests, more cooling is necessary to build up a sufficiently thick frozen slag layer to protect the slag screen tubes from the severe erosion/corrosion attack that can occur within the slag screen. The diameter of the stainless steel tubes installed in the slag screen tubes was 0.375 in. (0.952 cm) o.d. for lignite testing. However, when Illinois No. 6 coal is fired, the 0.375-in. (0.952-cm) o.d. water-cooled stainless steel tubes provide too much cooling, forcing higher auxiliary burner firing rates in order to maintain slag screen temperatures and desired slag flow. Therefore, the sizes of the stainless steel tubes are reduced to 0.25-in. (0.63-cm) o.d. for Illinois No. 6 bituminous coal firing. For fuels with more refractory ash, smaller tube sizes are required, and the number of slag screen tubes may also have to be reduced. At this time, insufficient data are available to determine which tube size is most appropriate for subbituminous coal. The slag screen tubes will likely always require periodic replacement based on some level of erosion/corrosion and the fuels selected for testing.

Mass balances were completed for all SFS operating periods in order to document the distribution of slag/ash in the system. Based on operating experience with bituminous coal, subbituminous coal, and lignite, 60% to 80% coal/lignite ash is captured in the SFS as slag. Fly ash recovered from other system components (drawdown gas line, CAH duct, process air preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping) represents 20% to 40% of the theoretical ash. Nominally 10% to 15% of the ash in the fuels fired in the SFS is reaching the baghouse. Specific modifications to the slag screen in support of this project as well as slag screen performance are summarized later in this report.

2.2.5 *Dilution/Quench Zone*

The dilution/quench zone design was a cooperative effort between the EERC and UTRC. The circular dilution/quench zone is oriented vertically, maintains a 1.17-ft (0.36-m) diameter in the area of the FGR nozzles and then expands the duct diameter to 2 ft (0.6 m) to provide adequate residence time within duct length constraints. The duct section containing the FGR nozzles is a spool piece in order to accommodate potential changes to the size, number, and orientation of the FGR nozzles. The vertically oriented dilution/quench zone is refractory-lined and located immediately downstream of the slag screen and upstream of the CAH duct.

Routine cleaning of the dilution/quench zone is required during each weeklong coal- or lignite-fired test. In order to monitor and document the slag deposition in the dilution/quench zone, a pressure transmitter is used to monitor and record differential pressure. On the basis of observations during a test in August 1998 and the frequent cleaning required, the EERC modified the spool piece section of the dilution/quench zone. The specific modification involved the addition of a water-cooled wall around the FGR nozzles. Subsequent operating experience indicates that the water-cooled wall embrittles the slag deposits that form in this area, making them more prone to spontaneous shedding and generally easier to remove on-line. Performance observations as a result of test periods completed in support of this project are summarized later in this report.

2.2.6 *Convective Air Heater*

The CAH design was a cooperative effort between the EERC and UTRC. It was constructed by UTRC and assembled and installed in September 1997. The flue gas flow rate to the CAH tube bank has been calculated by the EERC to range from 3553 to 4619 acfm at 1800°F (101 to 131 m³/min at 982°C) depending on the firing rate and fuel fired in the SFS. A rectangular inside duct dimension of 1.17 ft² (0.11 m²) results in a flue gas approach velocity of 50 to 73 ft/s (15 to 22 m/s) to the CAH tube bank. Heat is recovered from the flue gas to meet process air temperature requirements for the CAH. The design process air exit temperature from the CAH is 1200°F (649°C) and is not permitted to exceed 1300°F (705°C). Process air flow rate is used to control process air exit temperature using a flow control valve.

The CAH tube bank originally consisted of twelve 2-in. (5-cm)-diameter tubes installed in a staggered three-row array. The first five tubes in the flue gas path were uncooled ceramic material, with the remaining seven tubes cooled using heated air. The uncooled ceramic tubes were replaced in May 1998 with uncooled stainless steel tubes. Replacement of the ceramic tubes was necessary because the ceramic tubes were too easily damaged when the tube bank was removed from the duct after the test periods in February, March, and April 1998.

Prior to the August 1998 test, fins were added to the air-cooled tubes in the CAH to improve heat transfer. The fins are 1-in. (2.5-cm) by 0.125-in. (0.318-cm) flat material and run the length of each tube on both the leading and trailing edges of the tube surface. Based on the August 1998 and subsequent data, it appears that the addition of the fins improved heat recovery during coal-fired test periods. The fins appear to have reduced the rate of heat-transfer

degradation as ash deposits developed and helped to maintain a higher heat-transfer rate once the deposits had formed. However, no improvement in heat recovery was observed during natural gas-fired periods with clean tube surfaces.

In September 1998, the uncooled tubes were again replaced. The replacement tubes represented three high-temperature alloy types (Incoloy MA956, Incoloy MA956HT, and PM2000) and three pipe sizes (1.5-in. [3.8-cm] Schedule 80, 1-in. [2.5-cm] Schedule 40, and 0.75-in. [1.9-cm] Schedule 40, respectively). Figure 2-3 illustrates the position, size, and alloy type for the five uncooled tubes. There are no plans at this time to remove the uncooled tubes for characterization.

2.2.7 Process Air Preheaters

Process air required for operation of the CAH tube bank and the RAH panel is preheated in five high-temperature alloy tube bundles located in the flue gas stream downstream of the CAH tube bank. The first tube bundle supports operation of the CAH tube bank and the remaining four support the operation of the RAH panel. Because of flue gas temperatures (1700°F or 927°C) in the vicinity of the first three process air preheaters and a nominal operating air pressure of 150 psig (10.3 bar), stainless steel was not an option. An alloy capable of handling higher-temperature operation was required to maximize system flexibility and minimize the potential for material failure. Material options considered included a Haynes HR-120, HR-160, HA-230, and HA-556 and an RA253MA. Maximum temperatures for these five alloys at 150 psig (10.3 bar) are 1600°, 1750°, 1650°, 1750°, and 1650°F (871°, 955°, 899°, 955°, and 899°C), respectively. Based on material characteristics, availability, and cost, EERC personnel elected to

Figure 2-3. Illustration of the uncooled tubes in the CAH tube bank.

use the RA253MA (1650°F at 150 psig or 899°C at 10.3 bar) material for all five tube bundles exposed to flue gas and the HR-160 (1750°F at 150 psig or 955°C at 10.3 bar) material to transfer the heated process air to the RAH and CAH test sections. Use of the HR-160 alloy permitted the installation of electrical heaters to improve process air temperature control to the RAH and CAH test sections. The use of RA253MA and HR-160 in combination for the process air preheaters maximized system flexibility and minimized cost.

The tube bundles are mounted in a refractory-lined, vertically oriented, square duct. Duct dimensions are 12 in. by 12 in. (30.5 cm by 30.5 cm) with an overall duct length of 20.5 ft (6.2 m). Refractory installation for this section was completed using a combination of Narco Cast 60 high-density refractory and Harbison-Walker 26 insulating refractory. All inlet and outlet process air lines supporting the CAH tube bank are insulated. Process air lines supporting the RAH panel are insulated and electrically heated.

Operational performance of the process air preheater tube bundles, piping subsystem, and process control scheme has been very good. Because of higher flue gas flow rates during natural gas firing, the air temperature exiting the process air preheater tube banks is higher when compared to coal-fired periods at comparable process air flow rates. However, during coal firing, it is still possible to obtain exit temperatures of 1300°F (705°C) at process air flow rates of 200 scfm (5.7 m³/min), even though the heat-transfer rate degrades with ash deposition on the tube surfaces. Further heating of the process air entering the RAH panel is achieved electrically and by recovering heat from the CAH tube bank. In addition, air compressor system and power failures have been encountered resulting in the use of the nitrogen backup system. The nitrogen backup system has functioned as intended during these support system failures, supplying an emergency cooling media to the process air preheaters and ultimately supporting the CAH tube bank and RAH panel.

2.2.8 *Slagging Furnace System Heat Exchangers*

The pilot-scale SFS has four tube-and-shell heat exchangers for heat recovery and flue gas temperature control and two water-cooled heat exchangers to reduce the heat load on system fans. Their location in the overall process layout is illustrated in Figure 2-2. The first two tube-and-shell heat exchangers reduce flue gas temperature and preheat the secondary air for the main burner. The third and fourth tube-and-shell heat exchangers are used to control flue gas temperature at the inlet of the pulse-jet baghouse.

The tube-and-shell heat exchangers have performed up to expectations during all test periods. The main burner secondary combustion air temperature is nominally 600° to 800°F (316° to 427°C) depending on ambient air temperatures. During winter months, the secondary air temperature can be controlled at the lower end of the range and during summer months, temperature control is limited to the higher end of the range. Tube-and-Shell Heat Exchangers 3 and 4 perform very well, controlling the flue gas temperature at the baghouse inlet to <400°F (<205°C). Inspection during maintenance after each week of coal-fired operation indicates the presence of a scale-type ash layer on the surface of the tubes that must be removed in order to avoid deterioration of heat-transfer performance and corrosion of metal surfaces.

Two water-cooled heat exchangers were fabricated and installed in May 1998 to reduce the load on the FD (forced-draft), ID (induced-draft), and process air fans and ambient temperature on the upper levels of the SFS support structure. A water-cooled heat exchange tube bundle was installed in the flue gas stream between the five high-pressure process air preheater tube bundles and the first tube-and-shell heat exchanger. This water-cooled tube bundle reduces the cooling load on the FD and process air fans. A water-jacketed heat exchanger was installed on the secondary air bypass line to the stack to reduce the amount of heat being emitted to the immediate area and ambient temperature in the high bay in general.

2.2.9 System Fans

The pilot-scale SFS has five fans, a combustion air FD fan, two process air FD fans, an ID fan, and an FGR fan. Table 2-3 summarizes the fan specifications. All five are centrifugal-type fans, with variable-speed drives (speed controllers) installed on the four large fans. Valves and orifice plates and venturis are used to control and measure, respectively, the air and flue gas flow in the SFS. The small process air FD fan provides process air to the RAH panel door frame. The RAH door frame requires 100 scfm (2.8 m³/min) of process air. A valve and flow measurement device permits measurement and control of process air flow rate to the RAH door frame.

TABLE 2-3

Pressure, Temperature, and Flow Specifications for the SFS Fans

	Inlet Pressure, psig	Exit Pressure, psig	Avg. Inlet Temp., °F	Min. Inlet Temp., °F	Max. Inlet Temp., °F	Max. Inlet Flow, scfm	Max. Inlet Flow, acfm	Avg. Inlet Flow, acfm	Motor Horsepower
FD Fan	0	3	60	20	100	1200	1292	1200	40
Process Air Fan	0	1.5	60	20	100	1200	1292	1200	20
ID Fan	-1	1.5	350	250	450	1200	2255	1755	25
FGR Fan	0	1.5	350	250	450	450	788	701	10
Process Air Fan	0	2.0	80	60	100	200	200	200	5

2.2.10 Emission Control

A pulse-jet baghouse is used for final particulate control for the SFS. The baghouse design permits operation at both cold-side (250° to 400°F, 121° to 205°C) and hot-side (600° to 700°F, 316° to 371°C) temperatures. The primary baghouse chamber and ash hopper walls are electrically heated and insulated to provide adequate temperature control to minimize heat loss and avoid condensation problems on start-up and shutdown. The main baghouse chamber was designed with internal angle iron supports to handle a negative static pressure of 20 in. W.C. (37 mmHg).

Flue gas flow rates to the baghouse can range from a low of 630 scfm (17.8 m³/min) at 350°F (177°C), to a maximum of 1063 scfm (30.1 m³/min) at 700°F (371°C). Therefore, the baghouse design was based on an average flue gas flow rate of 850 scfm (24.1 m³/min) at 350°F (177°C) or 1900 acfm (53.8 m³/min) at 700°F (371°C), based on a nominal furnace firing rate of 2.5 MMBtu/hr (2.6 × 10⁶ kJ/hr). The baghouse is sized to accommodate a maximum of 36 bags mounted on wire cages with 2-in. (5-cm) bag spacing. Bag dimensions are nominally 6 in. (15.2 cm) in diameter by 10 ft (3.0 m) in length, providing a total filtration area of 565 ft² (52.5 m²).

Pulse-jet cleaning can be triggered as a function of baghouse differential pressure or as a function of time. The baghouse pulse-jet cleaning system is operated/controlled by a program written for the Genesis data acquisition software that permits adjustment of cleaning frequency and pulse duration. Timers in the software are used to set pulse duration and off time, while total baghouse operating time and test time in hours and total and test cleaning cycles are documented by EERC staff. Filter bag cleaning occurs when the controller opens the solenoid-operated valves between the pulse-air reservoir and the six pulse-air manifold lines. Each manifold line provides pulse air to six filter bags, which are cleaned simultaneously. There is a short pulse delay between each set of filter bags to allow air pressure to recover in the pulse-air reservoir. High-pressure/low-volume and low-pressure/ high-volume cleaning options were included in the design of the pulse-air system. During heatup and off-line cleaning, flue gas flow is diverted through a cyclone.

To date, only one tube sheet has been constructed, permitting the installation of 36 bags arranged in a six-by-six array. Installing the maximum number of bags permits the SFS to be operated over the broadest potential range of conditions while minimizing the potential impact of the baghouse on overall system performance. Each filter bag is secured to the tube sheet using a snap band sewn into the top cuff. Stainless steel (304 SS) wire cages with 20 vertical wires and 6-in. (15-cm) ring spacing provide bag support. The pulse-jet baghouse is a single compartment capable of either on- or off-line cleaning. Flue gas enters the baghouse in an area just below the bottom of the cage-supported bags and above the ash hopper. Access to the filter bags and stainless steel wire cages is gained by removing the clean air plenum at the top of the baghouse. The fabric type used during tests documented in this report was a 22-oz/yd² (744-g/m²) woven glass bag with a polytetrafluoroethylene (PTFE) membrane. Prior to the tests documented in this report, a 16-oz/yd² (543-g/m²) Huyck felt material was used. Baghouse performance observations as a result of this project are summarized later in this report.

The SFS does not have a sulfur dioxide control system, and there are no plans to install one at this time. Dispersion modeling data developed by the North Dakota State Health Department indicates that the stack height, flue gas velocity at the stack exit, and dilution effect of the system process air that is exhausted through the stack permits a maximum sulfur dioxide emission rate of 20.8 lb/hr (9.4 kg/hr). The SFS sulfur dioxide emission rate is limited to 20.8 lb/hr (9.4 kg/hr) to avoid the potential to exceed the 1-hour ambient air quality standard of 715 µg/m³. However, based on operating experience with bituminous and subbituminous coal and lignite, the EERC has never exceeded a sulfur dioxide emission rate of 18 lb/hr (8.2 kg/hr).

2.2.11 Instrumentation and Data Acquisition

The instrumentation and data acquisition components for the pilot-scale SFS address combustion air, flue gas, process air, process water, temperatures, static and differential pressures, and flow rates. The data acquisition system is based on a Genesis software package and three personal computers. Two sets of flue gas instrumentation (oxygen, CO₂, carbon monoxide, sulfur dioxide, and nitrogen species) are dedicated to support the operation of the SFS. Flue gas is transferred from the sample point through a heated filter and sample line to the sample conditioner before it reaches the analyzers. Flue gas is routinely sampled in the slag screen at the furnace exit and the exit of the baghouse. Total flue gas flow rate through the SFS is measured using a venturi.

2.3 Dynamic Slag Application Furnace

The DSAF, shown in Figure 2-4, is a modified double-chamber bench-scale furnace designed to simulate conditions of flowing (dynamic) slag corrosion on the vertical wall of a refractory-lined slagging combustor. It has the capability of testing refractory test samples up to a maximum of 2910°F (1600°C) and is designed to handle up to four test samples 4 in. by 4 in. by 9 in. (10 cm by 10 cm by 23 cm) simultaneously. A low-rate volumetric feeder transfers slag granules from the feeder hopper to the furnace through a set of double intermediate augers. The slag granules enter the furnace through four slag injector feed ports located on the top of the furnace and exit the furnace through two exit ports located on the bottom of the furnace. The spent slag is collected in a water quench vessel.

Figure 2-4. Schematic of the DSAF.

3.0 RESULTS AND DISCUSSION

Project results are documented in this section of the report. The results are discussed in terms of the pilot-scale SFS tests as well as the laboratory- and bench-scale activities. The discussion of pilot-scale results addresses fuel characteristics, the general performance of the pilot-scale SFS (slagging furnace, slag screen, dilution/quench zone, process air preheaters, and pulse-jet baghouse performance and flue gas emissions), and the performance of the CAH tube bank and RAH panel. Results are also presented on the DSAF testing of the chromia–alumina sintered brick material and on tests of coatings and sintering temperature on Plicast 98 castable refractory. In addition, results are presented on laboratory testing of modifications of slag viscosity by the use of slag additives. Conclusions based on the data are summarized as well as recommendations for further work where warranted.

3.1 Pilot-Scale Testing

The results of the three bituminous coal-fired test periods (January/SFS-RH6-0199, February/SFS-RH7-0299, and April/SFS-RH8-0399) completed in support of this task are documented in this section of the report. The slagging furnace operational periods involved planned natural gas firing to support the heatup and cooldown of the SFS and slag pot replacement, unplanned natural gas-fired periods as a result of a slag tap and slag screen plugging, and 299 hours of coal firing. Specific areas of discussion include fuel characteristics, SFS performance (slagging furnace, slag screen, dilution/quench zone, process air preheaters, and pulse-jet baghouse performance and flue gas emissions), CAH performance, RAH panel performance, and observations specific to the two bituminous coals fired and their impacts on HITAF performance.

3.1.1 Pilot-Scale SFS Performance

The pilot-scale SFS was fired on natural gas and Illinois No. 6 coal during the period January 24–29; on natural gas and an eastern Kentucky bituminous coal during the period February 14–19; and on natural gas, an eastern Kentucky coal, and Illinois No. 6 coal during the period April 4–16. The purpose of the January test was to 1) evaluate the RAH panel following its reassembly and installation in early January; 2) test a new high-density inner-layer refractory design while firing coal; and 3) test two refractory coatings painted on small areas of the high-density inner refractory layer to determine if they would help reduce slag corrosion of the refractory. The purpose of the February and April tests was to continue the evaluation of the RAH panel and increase the number of hours of exposure to slagging furnace conditions. The coal used in February was selected because of its significant commercial interest and because it presented significantly different ash/slag properties compared to the Illinois No. 6 coal. This section of the report summarizes the results and observations concerning three 1999 SFS tests as well as related SFS maintenance and modification activities.

Fuel Characteristics

The fuel feed system was operated in January (60 hours, Illinois No. 6 coal) at a nominal feed rate of 180 to 195 lb/hr (82 to 89 kg/hr), as illustrated in Figure 3-1. Nominal feed rate in February (38 hours, Kentucky bituminous coal) was 150 to 170 lb/hr (68 to 77 kg/hr), as shown in Figure 3-2. There were 201 hours of fuel feed operation in April while eastern Kentucky and Illinois No. 6 bituminous coals were fired. The EERC had planned to fire the eastern Kentucky coal for 200 hours. However, the quantity of available fuel was only adequate to complete 150 hours of coal firing. Therefore, Illinois No 6 coal was fired for the final 51 hours. Nominal feed rates were 150 to 160 lb/hr (68 to 73 kg/hr) for the eastern Kentucky coal and 190 to 205 lb/hr (86 to 93 kg/hr) for the Illinois No. 6 coal. Figure 3-3 illustrates the coal feed rate data for the April test. For all three tests, adjustments to coal feed rate were made in order to maintain a flue gas temperature near the RAH tile surfaces of 2800°F (1538°C). The coal feed rate was quite stable except for a few minor spikes (high and low) associated with coal hopper refill cycles.

For comparison purposes, Tables 3-1 and 3-2 are presented to summarize analytical results for the Illinois No. 6 bituminous, Kentucky bituminous, and Rochelle subbituminous coal and the Coal Creek Station (CCS) and Milton R. Young Station (MRYS) lignites, respectively, that have been fired in the pilot-scale SFS. For the January test (SFS-RH6-0199), the analyses of the composite Illinois No. 6 coal sample indicated that the as-fired fuel contained 5.1 wt% moisture, 11.3 wt% ash, and 3.7 wt% sulfur. The heating value was 11,328 Btu/lb (26,324 kJ/kg) on an as-

Figure 3-1. Coal feed rate versus run time for the January 1999 test, SFS-RH6-0199.

Figure 3-2. Coal feed rate versus run time for the February 1999 test, SFS-RH7-0299.

Figure 3-3. Coal feed rate versus run time for the April 1999 test, SFS-RH8-0399.

TABLE 3-1

Results of Coal and Coal Ash Analysis for Coal-Fired Slagging Furnace Tests ¹			
	Illinois No. 6 Bituminous Coal	Kentucky Bituminous Coal	Rochelle Subbituminous Coal
Proximate Analysis, wt%			
Moisture	4.4–10.3	2.3–2.5	21.6–24.3
Volatile Matter	35.9–39.5	38.2–38.7	35.6–37.4
Fixed Carbon	43.3–46.3	53.7–54.9	35.8–36.7
Ash	10.6–11.5	3.9–4.7	4.3–4.7
Ultimate Analysis, wt%			
Hydrogen	4.8–5.8	5.2–5.5	6.1–6.4
Carbon	61.6–64.9	77.5–78.2	53.0–55.2
Nitrogen	0.8–1.6	1.8	0.6–0.7
Sulfur	3.2–4.1	0.8–1.0	0.3
Oxygen	14.2–17.6	9.6–9.7	32.9–33.4
Ash	10.6–11.5	3.9–4.7	4.3–4.7
Heating Value, Btu/lb	11,015–11,658	13,861–14,120	9021–9328
Percent as Oxides, wt%			
SiO ₂	50.2–53.9	37.7–44.8	26.7–27.1
Al ₂ O ₃	19.8–21.2	28.9–29.8	15.5–16.3
Fe ₂ O ₃	13.6–16.0	13.7–14.5	6.3–6.6
TiO ₂	0.9	1.1	1.2–1.4
P ₂ O ₅	0.1–0.2	0.1	0.7–0.9
CaO	3.0–3.6	1.9–2.8	21.6–24.3
MgO	1.5–2.0	2.1–2.4	6.7–6.9
Na ₂ O	1.1–1.4	1.1–1.3	1.5
K ₂ O	1.9–2.1	2.7–3.0	0.1–0.4
SO ₃	2.5–4.0	2.4–3.8	15.6–17.0
Ash Fusion Temp., °F			
Initial	2315–2361	2398–2577	2202–2295
Softening	2342–2417	2440–2603	2205–2308
Hemispherical	2392–2448	2474–2621	2214–2311
Fluid	2491–2534	2588–2684	2221–2325
Sieve Analysis			
Screen Mesh Size	Weight Percent Retained		
100	1.8–25.2	8.1–11.4	7.6–8.8
140	0–14.9	12.9–13.9	14.2–15.4
170	0–14.9	NA ²	NA
200	9.6–13.5	11.4–13.5	14.3–14.4
230	0–16.2	8.7–9.4	8.4–9.1
270	0.5–14.6	0.7–1.6	2.0–5.6
325	7.4–14.7	11.9–12.7	4.8–11.6
400	0–4.7	NA	NA
Pan	29.7–57.8	41.2–42.6	39.7–43.4
Total %	99–100.2	99.9–100.1	98.6–100.6

¹ Coal analysis is presented on an as-fired basis.² Not available.

TABLE 3-2

Results of Lignite and Lignite Ash Analysis for Lignite-Fired Slagging Furnace Tests¹

	Coal Creek Station Lignite	Milton R. Young Station Lignite
Proximate Analysis, wt%		
Moisture	31.6–37.9	33.8–37.1
Volatile Matter	29.4–31.5	30.4–32.1
Fixed Carbon	26.4–26.8	26.9–27.9
Ash	6.3–10.2	5.6–6.2
Ultimate Analysis, wt%		
Hydrogen	6.4–6.8	7.0–7.2
Carbon	38.5–40.9	41.1–43.4
Nitrogen	0.6	0.6
Sulfur	0.5–0.7	0.7–0.9
Oxygen	41.1–47.3	42.1–44.9
Ash	6.3–10.2	5.6–6.2
Heating Value, Btu/lb	6300–6708	6933–7144
Percent as Oxides, wt%		
SiO ₂	31.8–35.5	11.2
Al ₂ O ₃	11.7–12.0	8.6
Fe ₂ O ₃	6.4–8.0	13.2
TiO ₂	0.5	0.2
P ₂ O ₅	0.3	0.1
CaO	17.0–18.7	21.3
MgO	6.5–7.0	7.3
Na ₂ O	2.9–3.2	11.7
K ₂ O	1.3	0.2
SO ₃	16.0–19.0	26.2
Ash Fusion Temp., °F		
Initial	2170–2188	2370–2371
Softening	2181–2196	2381–2384
Hemisphere	2189–2203	2384–2387
Fluid	2196–2219	2392–2428
Sieve Analysis		
Screen Mesh Size	Weight Percent Retained	
100	6.4–10.3	14.9
140	12.3–13.8	15.7
170	NA ²	4.6
200	11.9–12.3	8.5
230	3.7–8.5	NA
270	6.2–10.2	3.1
325	6.4–6.5	14.9
400	NA	NA
Pan	41.5–48.2	38.2
Total %	98.3–99.9	99.9

¹ Lignite analysis is presented on an as-fired basis.² Not available.

fired basis. Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2417°F (1325°C) and a fluid temperature of 2491°F (1366°C).

For the February test (SFS-RH7-0299), the analyses of the composite Kentucky coal sample indicated that the as-fired fuel contained 2.5 wt% moisture, 3.9 wt% ash, and 0.8 wt% sulfur. The heating value was 14,120 Btu/lb (32,812 kJ/kg) on an as-fired basis. Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2440°F (1338°C) and a fluid temperature of 2588°F (1420°C). The fluid temperature of the Kentucky coal ash during this test period was 50°F (28°C) higher than any of the previous fuels fired.

For the April test (SFS-RH8-0399), the analyses of the composite Kentucky coal sample indicated that the as-fired fuel contained 2.3 wt% moisture, 4.7 wt% ash, and 1.0 wt% sulfur. The heating value was 13,861 Btu/lb (32,210 kJ/kg) on an as-fired basis. Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2603°F (1429°C) and a fluid temperature of 2684°F (1474°C). The fluid temperature of the Kentucky coal ash was >100°F (56°C) higher than any of the previous fuels fired. The Illinois No. 6 as-fired fuel contained 4.4 wt% moisture, 11.2 wt% ash, and 3.6 wt% sulfur. The heating value was 11,257 Btu/lb (26,159 kJ/kg). Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2396°F (1314°C) and a fluid temperature of 2518°F (1381°C).

A comparison of the two bituminous coals shows that the Illinois No. 6 coal contains significantly more moisture, four times the sulfur, and nearly three times the ash. As a result of these fuel characteristics, the heating value of the Kentucky coal is 21%–26% greater than that of the Illinois No. 6 coal. Ash fusion temperatures were significantly higher for (100° to 200°F, 56° to 111°C) the Kentucky coal ash. Ash chemistry directly affects ash fusion temperature. Therefore, ash chemistry mineral size and composition data as they relate to slag properties are addressed in some detail in the slag screen performance discussion of this section (pages 37–45).

Dry-sieve analysis indicated that the pulverized Illinois No. 6 coal used in the January test was nominally 80 wt% –200 mesh (74 µm). While the same fuel fired in April was nominally 50 wt% –200 mesh (74 µm). Typically, the Illinois No. 6 coal is at least 70 wt% –200 mesh (74 µm). The EERC investigated possible reasons for the change in pulverizer performance but could not find an obvious explanation. This investigation is continuing. Dry-sieve analysis data for the pulverized Kentucky coal used in February and April indicated nominally 64 and 65 wt% –200 mesh (74 µm), respectively. The generally poorer pulverization performance for the Kentucky bituminous coal is believed to have been caused by surface moisture. However, because of the high furnace operating temperature, combustion efficiency was not generally affected by variations in pc particle size. For both fuels, the carbon content of the fly ash collected in the baghouse was low, 0.50 wt% for the Illinois No. 6 coal and 0.24–0.7 wt% for the Kentucky coal.

XRF analysis results for the various ashed fuels are summarized in Tables 3-1 and 3-2 and reported as oxides. Comparison of the Illinois No. 6 and Kentucky coal ash indicates that the

Kentucky coal ash contains significantly less silica, somewhat less iron, significantly more alumina, and slightly more magnesium and potassium. These ash properties are consistent with the differences in ash fusion temperatures observed.

Kentucky coal ash analysis indicates that the Kentucky coal fired in April had a somewhat different ash composition than the Kentucky coal fired in February. Although these compositional differences (higher silica and alumina and lower iron and calcium) appear small, they did result in significant differences in the ash fusion properties of the coal ash. With the exception of the fluid temperature, ash fusion temperatures were $>100^{\circ}\text{F}$ (56°C) higher for the April coal ash sample versus the February coal ash sample. The fluid temperature difference was nearly 100°F (56°C). The impact of the higher ash fusion temperatures observed in April are discussed later with respect to the performance of the slag screen (pages 37–45).

Slagging Furnace Operation

The slagging furnace heatup rate during the 1999 test periods was limited to 100°F/hr (56°C/hr) while natural gas was fired. This is the heatup rate recommended for the RAH panel by UTRC. In order to sinter anticorrosion coatings placed on the surface of the high-density refractory prior to the January test, the natural gas firing rate through the main burner was increased to 3.2 MMBtu/hr ($3.3 \times 10^6\text{ kJ/hr}$) in an attempt to achieve a furnace temperature of 2950°F (1621°C). Although this natural gas firing rate was maintained for nearly 2 hours, measured furnace temperature near the wall never exceeded 2900°F (1594°C). Further increases in the main burner natural gas firing rate were not possible because of ID fan limitations. Subsequently, the main burner natural gas firing rate was reduced to 2.3 MMBtu/hr ($2.4 \times 10^6\text{ kJ/hr}$) in order to reduce the furnace temperature to 2800°F (1538°C). When the furnace reached normal operating temperature ($2800^{\circ}\text{F}/1538^{\circ}\text{C}$), the main burner was switched from natural gas to coal firing. The coal-firing rate through the main burner in January was 2.1 to 2.25 MMBtu/hr (2.2 to $2.3 \times 10^6\text{ kJ/hr}$) with an auxiliary burner firing rate of 0.65 to 0.80 MMBtu/hr (0.7 to $0.9 \times 10^6\text{ kJ/hr}$). These firing conditions were maintained for 60 hours while attempting to maintain a furnace flue gas temperature near the RAH panel of 2800°F (1538°C). This temperature measurement was made using an optical pyrometer with secondary measurements using Type S thermocouples. Summaries of furnace and slag screen temperatures for the January test are presented as a function of run time in Figure 3-4, and the corresponding slagging furnace firing rate data are summarized in Figure 3-5.

During the week of January 24–29 (SFS-RH6-0199), the furnace was fired on Illinois No. 6 bituminous coal and the main burner swirl setting maintained at a minimum. No attempt was made to maximize and minimize the main and auxiliary burner firing rates, respectively, because of slag damming/flow problems in the slag screen. The total furnace firing rate (main plus auxiliary burners) ranged from 2.9 to 3.0 MMBtu/hr (3.0 to $3.1 \times 10^6\text{ kJ/hr}$). The main burner-firing rate accounted for 73% to 77% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2775° to 2840°F (1524° to 1560°C).

Figure 3-4. Furnace and slag screen temperatures versus run time for the January 1999 test, SFS-RH6-0199.

Figure 3-5. Slagging furnace firing rate versus run time for the January 1999 test, SFS-RH6-0199.

Furnace refractory temperatures ranged from 1060° to 1300°F (571° to 705°C) for the hot side of the insulating refractory to as high as 2480°F (1360°C) for the cold side of the high-density refractory. Compared to previous test periods with the Illinois No. 6 coal, the insulating refractory temperatures are 15° to 100°F (8° to 56°C) lower, and high-density refractory temperatures are 160°F (89°C) lower. The lower insulating refractory temperatures are probably the result of the planned gap/air space between the high-density and intermediate refractory layers. However, there is no obvious explanation for the lower cold-side high-density refractory temperature. One possibility is poor temperature data because of aging thermocouples. All of the thermocouples measuring furnace refractory temperatures were inspected following the test, and no replacements were required. Another possibility relates to the new high-density refractory installed and its emissivity or reflectivity properties. This issue and its potential implications will be discussed further later in this report concerning the performance of the RAH panel (Section 3.1.3).

Operating problems encountered during the January test were related to slag screen performance, which is addressed later in this report. During the January test, the slag tap never plugged and slag flow was not a problem. The refractory in the slag tap was replaced in the fourth quarter of 1998 in conjunction with the replacement of the high-density refractory furnace liner. As reported in the October through December 1998 quarterly technical progress report, the inner liner was poured in such a way that it would not bond to the middle refractory layer and would be in approximately 2-ft-square sections to allow it to move independently during heatup and cooldown. This design was very successful in preventing the extensive cracking that was seen in

the original furnace liner, so extensive patching was not required following the January test. Also, the slag tap was found to be in good condition and no repairs required prior to the February test.

The main burner natural gas firing rate was nearly 3.0 MMBtu/hr (3.1×10^6 kJ/hr) during preheating of the furnace prior to switching to coal firing during the February test. The coal firing rate through the main burner in February was 2.1 to 2.3 MMBtu/hr (2.2 to 2.4×10^6 kJ/hr) once the furnace refractory reached thermal equilibrium, with an auxiliary burner firing rate of 0.48 to 0.60 MMBtu/hr (0.6 to 0.7×10^6 kJ/hr). These firing conditions were maintained for 38 hours of coal firing while attempting to maintain a furnace flue gas temperature of 2800°F (1538°C) near the RAH panel. Summaries of furnace and slag screen temperatures for the February test are presented as a function of run time in Figure 3-6, and the corresponding slagging furnace firing rate data are summarized in Figure 3-7.

During the week of February 14–19 (SFS-RH7-0299), the furnace was fired on an eastern Kentucky bituminous coal, and the main burner swirl setting was maintained at a minimum. A modest attempt was made to maximize and minimize the main and auxiliary burner firing rates, respectively, near the end of the week. However, because of plugging problems in the slag screen, the effort was limited. The total furnace firing rate (main plus auxiliary burners) ranged from 2.7 to 2.9 MMBtu/hr (2.8 to 3.0×10^6 kJ/hr). The slightly lower total firing rate in February was due to a lower auxiliary burner firing rate required to maintain desired slag screen temperatures, possibly the result of the lower moisture content of the eastern Kentucky coal (2.5 versus 5.1 wt%). The main burner firing rate ranged from 2.1 to 2.27 MMBtu/hr (2.2 to 2.3×10^6 kJ/hr), accounting for 78% to 82% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2775° to 2830°F (1524° to 1555°C).

Furnace refractory temperatures ranged from 1080° to 1320°F (582° to 716°C) for the hot side of the insulating refractory to as high as 2490°F (1366°C) for the cold side of the high-density refractory. Compared to the January test with the Illinois No. 6 coal, the refractory temperatures are 10° to 20°F (6° to 11°C) higher. These slightly higher refractory temperatures may be the result of fuel moisture differences or possibly changes in the emissivity, reflectivity, or conductivity of the high-density refractory layer with exposure to slag.

Operating problems encountered during the February test were related to slag screen performance. Slag screen observations will be addressed later in this report. Following the February test, the high-density refractory lining the furnace was found to be in excellent condition without the cracking observed in the previous liner. Also, slag flow through the slag tap was not a problem during the test. The slag tap was found to be in good condition, and no repairs were required prior to the April test.

During the weeks of April 4–15 (SFS-RH8-0399), the furnace was fired with eastern Kentucky coal for 150 hours and Illinois No. 6 coal for 51 hours. The main burner swirl setting was maintained at a minimum, about 20%, for both fuels. After 184 hours of continuous coal firing, it was necessary to switch to natural gas firing in the main burner in order to facilitate the

Figure 3-6. Furnace and slag screen temperatures versus run time for the February 1999 test, SFS-RH7-0299.

Figure 3-7. Slagging furnace firing rate versus run time for the February 1999 test, SFS-RH7-0299.

replacement of the slag pot. Once the slag pot was changed, coal firing resumed for an additional 17 hours to complete the 200-hour test. If it had not been necessary to switch to the Illinois No. 6 coal, the 200-hour test could have been completed without having to change out the slag pot. The total furnace firing rate (main plus auxiliary burners) ranged from 2.7 to 2.8 MMBtu/hr (2.8 to 2.9×10^6 kJ/hr). The main burner firing rate ranged from 2.1 to 2.2 MMBtu/hr (2.2 to 2.3×10^6 kJ/hr), accounting for 76% to 81% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2740° to 2830°F (1505° to 1555°C). Summaries of furnace and slag screen temperatures are presented as a function of run time in Figure 3-8 for the April test. Corresponding slagging furnace firing rate data are summarized in Figure 3-9.

Furnace refractory temperatures ranged from 1055° to 1300°F (569° to 705°C) for the hot side of the insulating refractory to as high as 2430°F (1333°C) for the cold side of the high-density refractory. Compared to the February test period with the eastern Kentucky coal, the insulating refractory temperatures are 20°F (11°C) lower, and high-density refractory temperatures are 60°F (33°C) lower. These lower refractory temperatures appear to be the result of a narrower firing rate range in April, 2.7 to 2.8 MMBtu/hr (2.8 to 2.9×10^6 kJ/hr) versus 2.7 to 2.9 MMBtu/hr (2.8 to 3.0×10^6 kJ/hr) in February. Higher firing rates were unsuccessfully used in February to raise the slag screen temperature in an attempt to mitigate the slag plugging that was encountered.

Figure 3-8. Furnace and slag screen temperatures versus run time for the April 1999 test, SFS-RH8-0399.

Figure 3-9. Slagging furnace firing rate versus run time for the April 1999 test, SFS-RH8-0399.

No operating problems were encountered during the April test. Mitigating steps taken to avoid the slag screen performance problems encountered in February are addressed later in this report. During the April test, slag flow through the slag tap was not a problem. Excess slag deposits were found in the slag tap at the conclusion of the April test as a result of very viscous slag flowing from the slag screen during cooldown. However, these deposits did not plug the slag tap. The deposits were removed from the slag tap as a function of routine maintenance. The refractory in the slag tap was last replaced in the fourth quarter of 1998 in conjunction with the replacement of the high-density refractory furnace liner.

Minor pressure surges (a few inches of W.C.) are not uncommon in the slagging furnace. They happen on a periodic basis as a result of baghouse cleaning, opening of access ports to clean the dilution/quench zone and CAH tube bank, opening of access ports to insert or remove sampling probes, and when flue gas flow distribution through the baghouse or cyclone is altered. However, pressure surges in the furnace did not cause any operating problems during the test periods completed in January, February, and April 1999.

Inspection of the furnace refractory after the January, February, and April tests indicated that the new high-density refractory was in excellent condition. The only area showing any deterioration was below the RAH panel where slag from the panel was dripping onto the horizontal surface below. However, no refractory repairs/replacement were determined to be necessary. In addition, the approach used to install the new high-density refractory prior to the January test apparently eliminated the cracking observed immediately after the original high-

density refractory was cured. The only observed change in the high-density liner as a function of operation is that the color appears to get a little darker with each test, indicating slag penetration into the refractory. This change in appearance may indicate the potential for a failure of the high-density furnace liner if the refractory chemistry is sufficiently modified. However, the degree of slag impaction on the vertical walls is believed to be small, and there are no plans at this time to expose this refractory liner to low-melting-temperature slag.

The coatings applied to specific areas of the high-density refractory surface to improve its slag corrosion resistance prior to the January test were not evident upon furnace inspection following the test. Apparently, the coatings were eroded from or absorbed into the surface of the high-density refractory. The two coatings tested in the slagging furnace were selected based on bench-scale observations. Based on the pilot-scale observations, further bench-scale development work is necessary before additional coating tests will occur in the pilot-scale slagging furnace.

Main and Auxiliary Burners

The main and auxiliary burners performed well during the 1999 tests. As previously stated, the main burner swirl was maintained at a minimum (about 20%), while the auxiliary burner swirl setting was nominally 80%. Carbon efficiency for both bituminous coals was 99.3% or greater because of the high furnace operating temperature. Based on slagging furnace operating experience, the EERC intends to continue minimum main burner swirl as necessary to establish a stable flame, to establish uniform temperatures over the length of the furnace, and to minimize NO_x emissions.

Slag Screen Performance and Slag Analysis

Because the eastern Kentucky bituminous coal's higher ash fusion temperature, slag screen performance was negatively affected. Specific impacts observed included slag accumulation and plugging of the slag screen resulting in high slag screen differential pressure and a forced SFS shutdown in February 1999. These slag screen performance problems were effectively mitigated during the April 1999 test by injecting a small quantity of limestone along with the pulverized fuel.

Slag screen flue gas temperatures during the January test were typically 2585° to 2655°F (1419° to 1458°C) at the inlet and 2550° to 2600°F (1399° to 1427°C) at the outlet. Slag screen operating temperature is selected on the basis of ash fusion data for the fuel to be fired. The EERC tries to operate the slag screen at flue gas temperatures of 100° to 200°F (56° to 112°C) above the fluid temperature of the fuel ash to ensure slag flow from the slag screen to the slag tap. The ash fluid temperature (under oxidizing conditions) of the composite sample of Illinois No. 6 coal analyzed following the January test period was determined to be 2491°F (1366°C). A composite slag sample collected from the slag pot was found to have a fluid temperature of 2545°F (1396°C).

Figure 3-10 presents a photograph of the slag screen inlet following the January test. Erosion/corrosion of the slag screen tubes is evident along with some accumulation of slag on the

Figure 3-10. Photograph of slag screen tubes following the January test.

floor of the slag screen in the vicinity of the third and fourth rows of tubes. Partial plugging of the slag screen did occur during the January test. However, once the slag began to flow into the dilution/quench zone, slag screen operation remained stable at an elevated differential pressure, 3 to 7 in. W.C. (5.6 to 13.1 mmHg). Normally, the slag screen differential pressure is 2 in. W.C. (3.7 mmHg). Once coal feed was terminated, the slag screen differential pressure decreased over the 4-hour period of natural gas firing as slag slowly flowed to the slag tap. As a result, there was no need to complete extensive maintenance or repairs to the slag screen following the January test.

Following the January test, slag and ash samples from system components and piping were collected and weighed in order to prepare a mass balance. A total theoretical ash quantity was calculated (1258 lb or 570 kg) on the basis of the total coal feed and the measured ash content of the composite coal sample. Total slag and ash recovery from the January test was 81% (1019 lb or 463 kg). Slag recovery from the furnace, slag pot, and dilution/quench zone represented 71% of the theoretical ash. Additional slag was evident on the furnace wall, on the RAH panel, in the bottom of the furnace, in the slag screen, and in the upper section of the dilution/quench zone. However, this material is not recoverable from the high-density refractory. The EERC estimates that this unrecoverable slag may represent as much as 10% of the theoretical ash. Collected material and these estimates indicate that over 80% of the coal ash was captured in the system as slag.

Fly ash recovered from other system components (drawdown gas line, CAH duct, process air preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping)

represented 12% of the theoretical ash for the January test. Nominally, 10% to 15% of the ash in the fuels fired in the SFS has been reaching the baghouse. However, the baghouse ash recovered following the January test period represented <5% of the total ash/slag. While the bags were not removed from the baghouse and thoroughly cleaned following the January test, the residual dust cake on the bags is not likely to increase the baghouse ash to more than 7% of the total.

Figure 3-11 is a photograph of the slag screen inlet following the February test, showing that the first row of tubes experienced additional erosion/corrosion, as well as significant slag buildup on the floor of the slag screen in the vicinity of the second, third, and fourth rows of tubes. As the degree of slag screen plugging developed, differential pressure eventually exceeded 8 in. W.C. (14.9 mmHg), forcing a termination of the coal feed after 36 hours. After a number of hours of natural gas firing, the slag screen differential pressure decreased to 4.5 in. W.C. (8.4 mmHg). The differential pressure reduction during this period of natural gas firing was the result of a reduction in the auxiliary burner firing rate and possibly slag flow from the slag screen to the slag tap. The auxiliary burner firing rate was reduced while a consistent temperature was maintained in the slag screen by increasing the main burner natural gas firing rate. However, after nearly 3 additional hours of coal feed, slag screen differential pressure again exceeded 8 in. W.C. (14.9 mmHg), and termination of coal feed was again required.

The composition of the Kentucky coal ash as compared to the compositions of slag samples collected from the slag pot and slag screen following the February test are shown in Tables 3-3 and 3-4. The oxide values are reported on an oxide basis normalized to an SO₃-free

Figure 3-11. Photograph of slag screen tubes following the February test.

TABLE 3-3

February Kentucky Coal Ash, Slag Pot, and Slag Tap Samples				
Oxides, ¹ wt%	Kentucky Coal	Pot Bottom	Pot Top	Slag Tap
SiO ₂	40.4	45.6	43.6	46.8
Al ₂ O ₃	30.8	23.6	27.7	26.9
Fe ₂ O ₃	10.6	16.4	17.4	17.9
TiO ₂	1.1	1.0	0.9	0.9
P ₂ O ₅	0.1	0.1	0.1	0.1
CaO	10.9	6.6	4.9	2.0
MgO	2.3	4.0	2.5	1.9
Na ₂ O	1.5	1.0	1.1	1.0
K ₂ O	2.3	1.7	1.9	2.6
SO ₃ ²	6.7	0.1	0.1	0.1

¹ Oxide concentrations normalized to an SO₃-free basis.

² SO₃ concentrations normalized with other oxides.

TABLE 3-4

February Kentucky Coal Ash and Slag Screen Samples				
Oxides, ¹ wt%	Kentucky Coal	Screen Front	Screen Back	Quench Entrance
SiO ₂	40.4	49.5	48.2	49.4
Al ₂ O ₃	30.8	26.4	28.3	25.1
Fe ₂ O ₃	10.6	15.6	13.9	11.1
TiO ₂	1.1	1.0	1.1	0.9
P ₂ O ₅	0.1	0.1	0.0	0.1
CaO	10.9	1.9	2.7	8.0
MgO	2.3	1.9	2.2	1.9
Na ₂ O	1.5	1.1	1.2	1.7
K ₂ O	2.3	2.6	2.3	1.9
SO ₃ ²	6.7	0.1	0.1	0.1

¹ Oxide concentrations normalized to a SO₃-free basis.

² SO₃ concentrations normalized with other oxides.

basis, while the SO₃ numbers are reported on a basis normalized with the other oxides. The slag pot samples were collected from the bottom and top of the slag collected in the pot and from the slag tap itself to determine if the composition of the slag dripping into the pot changed during the

course of the test. This was done in order to explain why the slag initially flowed quickly into the pot from the slag screen, but later in the test it appeared to become more viscous, ultimately leading to the formation of the slag dam.

The data show that all of the slag samples contained much less calcia, slightly less alumina, slightly more silica, and much more iron oxide than the original coal ash. CCSEM analyses of the minerals in the coal indicate that the alumina and silica in the coal were concentrated in clay particles, with the larger clay particles being more enriched in silica compared to the smaller clay particles. The calcia in the coal was concentrated in larger limestone particles and the iron in larger pyrite particles. The reduced alumina content in the slag pot samples most likely occurred because the smaller, alumina-rich clay particles stayed entrained in the gas stream as it passed around the slag screen tubes rather than impacting the tubes. The alumina content in the slag did increase, however, as the run proceeded, possibly because the slag screen efficiency increased slightly, causing more of the smaller clay-derived particles to be captured. The lower calcia content in the slag samples as compared to the coal ash is most likely due to the limestone fragmenting on heating, forming small particles that also passed around the tubes. Note that the calcia content did not increase in the samples collected higher in the pot, indicating that any increase in capture efficiency later in the test was not enough to begin significant capture of limestone-derived particles. The enrichment in iron oxide in the slag is due to the high capture efficiency for the relatively large pyrite-derived ash particles.

The compositions of the residual slag held in dams in the slag screen itself are compared to that of the coal ash in Table 3-4. As is true for the slag pot samples, the slag dams are depleted in alumina and calcia and enriched in silica and iron. However, the enrichment in silica is greater than, and the iron less than, the enrichments found in the slag pot samples. These changes would give the slag dam samples even higher viscosities than the slag pot samples. However, slag flow patterns in the main furnace indicate that essentially all of the slag in the slag pot flowed from the slag screen. The fact that the higher-viscosity slag remained in the screen and the lower-viscosity slag flowed out into the pot may indicate that the slag is a mixture of high- and low-viscosity materials.

Because of the large amount of residual slag left in the slag screen following the February test, the EERC elected to rebuild the slag screen prior to the April test. In order to improve the performance of the slag screen when the Kentucky bituminous coal was fired, only three rows of tubes were installed (1, 3, and 5). Eliminating three rows of tubes was meant to accomplish three objectives: 1) reduce the heat loss in the slag screen, 2) reduce the collection efficiency of the slag screen, and 3) lessen the drag on the flow of the slag out of the screen. Reducing the heat loss in the slag screen was expected to result in a higher slag temperature and a lower slag viscosity, improving slag flow from the slag screen to the slag tap. Reducing the collection efficiency of the slag screen would permit smaller alumina and silica-rich clay-derived slag particles to escape to the dilution/quench zone and CAH section of the SFS.

Following the February test, slag and ash samples were again collected from system components and piping and weighed in order to prepare a mass balance. A total theoretical ash quantity was calculated (230 lb or 104 kg) on the basis of the total coal feed and the measured ash

content of the composite coal sample. Total slag and ash recovery from the February test was only 71% (163 lb or 74 kg). Slag recovery from the furnace, slag pot, and dilution/quench zone represented nominally 53% of the theoretical ash. Based on previous experience and inspection following the February test, additional slag appears to have been adsorbed/absorbed into the furnace wall, collected in the slag screen, and collected in the upper section of the dilution/quench zone. However, this material is not recoverable from the high-density refractory. The EERC estimates that this unrecoverable slag may represent as much as 25% of the theoretical ash in this case because of the plugging in the slag screen. Collected material and these estimates indicate that over 75% of the coal ash was captured in the system as slag. The 71% closure on ash and slag for the February Kentucky coal test is less than the January Illinois No. 6 test as well as most other bituminous coal-fired tests. The reason for the generally poorer closure in February was due to the slag dam in the slag screen and an inability to recover this slag exclusive of the refractory for inclusion in the mass balance.

Fly ash recovered from other system components (drawdown gas line, CAH duct, process air preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping) represented 18% of the theoretical ash for the February test. For most SFS tests, 10% to 15% of the ash in the fuels fired in the SFS has been reaching the baghouse. Baghouse ash recovered following the February test period represented about 10% of the total ash/slag. Again, the bags were not removed from the baghouse and thoroughly cleaned following the February test. However, the residual dust cake on the bags would likely be comparable to that present following the January test. Therefore, recovery of the ash from the bags would not be an appropriate contribution to the February mass balance.

Slag screen flue gas temperatures during the April test when the eastern Kentucky coal was fired were typically 2650° to 2700°F (1455° to 1483°C) at the inlet and 2600° to 2700°F (1427° to 1483°C) at the outlet. After we switched to the Illinois No. 6 coal, slag screen flue gas temperatures were typically 2600° to 2670°F (1427° to 1466°C) at the inlet and 2570° to 2650°F (1410° to 1455°C) at the outlet. The ash fluid temperature (under oxidizing conditions) of the composite samples of eastern Kentucky and Illinois No. 6 coal analyzed following the April test period was determined to be 2684°F (1474°C) and 2518°F (1381°C), respectively.

Because of the high ash fusion temperature of the eastern Kentucky coal ash, slag screen differential pressure began to increase as soon as coal firing began. In order to modify the slag chemistry and reduce its ash fusion temperature, control slag screen differential pressure, and avoid plugging problems, a feed system was set up to add -40-mesh (-370 µm) limestone to the coal at the point it entered the primary air stream. The effectiveness of the limestone addition was evaluated for limestone feed rates ranging from 0.25 to 2 lb/hr (113 to 908 g/hr). An initial limestone feed rate of 1 lb/hr (454 g/hr) was used, and slag screen differential pressure began to decrease immediately. However, after a few hours, slag screen differential pressure began to rise again. A check of the limestone feeder revealed that the screw had stopped turning. The screw feeder was subsequently repaired, and the limestone feed was increased to 2 lb/hr (908 lb/hr). Again, the slag screen differential pressure immediately decreased as limestone feed was initiated. Subsequent test periods were completed at limestone feed rates of 1.25, 1.0, 0.75, 0.5, and 0.25 lb/hr (568, 454, 340, 227, and 114 g/hr). Ultimately, slag screen differential pressure was

stabilized and effectively controlled at 0.5 in. W.C. (0.9 mmHg) using a limestone feed rate of 0.5 lb/hr (227 g/hr). Figure 3-12 presents slag screen differential pressure as a function of run time for the April test (SFS-RH8-0399). The 0.5 lb/hr (227 g/hr) limestone feed rate increased the total solids rate into the slagging furnace by nominally 0.3 wt%. The corresponding increase in the ash rate into the slagging furnace was nominally 3.7 wt% based on the calcium oxide addition to the ash.

The composition of the eastern Kentucky coal ash as compared to the composition of slag samples collected from the slag pot during the individual limestone injection tests is shown in Table 3-5. Analyses were completed for limestone feed rates of 0.25, 0.5, 1, and 2 lb/hr (114, 227, 454, and 908 g/hr). The oxide values for the slag samples are reported on a normalized oxide basis, while the coal ash sample is normalized to an SO₃-free basis.

As expected, the data show that the calcia content of the slag samples increased with increased limestone feed rate relative to the coal ash chemistry. However, the calcia content did not increase as much as it would have if the limestone were depositing in the slag at the same rate as the coal ash, indicating some limestone fragmentation. Also, the composition of the slag was sufficiently variable that a direct dilution effect for other slag components was not consistently evident in the samples. Ash fusion temperature data generated under oxidizing conditions did show the desired effect of limestone addition to the fuel. The highest ash fusion temperatures were observed for the coal ash, with ash fusion temperatures decreasing as the limestone feed rate was increased.

Figure 3-12. Slag screen differential pressure versus run time for the April 1999 test, SFS-RH8-0399.

TABLE 3-5

April Kentucky Coal Ash and Slag Tap Samples					
Oxides, ¹ wt%	Kentucky Coal Ash ²	Limestone, 2 lb/hr	Feed, 1 lb/hr	Rate, 0.5 lb/hr	Rate, 0.25 lb/hr
SiO ₂	45.9	43.4	42.2	44.6	44.8
Al ₂ O ₃	29.6	28.4	30.1	27.9	26.2
Fe ₂ O ₃	14.8	14.5	15.2	16.4	19.9
TiO ₂	1.1	1.0	0.9	0.9	1.0
P ₂ O ₅	0.1	0.1	0.1	0.1	0.1
CaO	2.0	7.1	6.1	5.0	2.6
MgO	2.3	2.2	2.2	2.2	2.0
Na ₂ O	1.1	0.8	0.7	0.7	0.6
K ₂ O	3.1	2.4	2.3	2.2	2.9
SO ₃	—	0.1	0.1	0.1	0.1
Ash Fusion Temp., °F					
Initial	2577	2436	2441	NM ³	NM
Softening	2603	2441	2446	NM	NM
Hemisphere	2621	2467	2474	NM	NM
Fluid	2684	2537	2537	NM	NM

¹ Oxide concentrations normalized to 100% closure.

² SO₃-free basis.

³ Not measured.

Following the April test, slag and ash samples from system components and piping were collected and weighed in order to prepare a mass balance. A total theoretical ash quantity was calculated (2273 lb or 1032 kg) on the basis of the total coal feed and the measured ash content of the composite coal samples and the quantity of calcium oxide introduced as limestone. Total slag and ash recovery from the April test was 86% (1958 lb or 889 kg). Slag recovery from the furnace, slag pot, and dilution/quench zone represented 69% of the theoretical ash. Additional slag was evident on the furnace wall, on the RAH panel, in the bottom of the furnace, in the slag screen, and in the upper section of the dilution/quench zone. However, this material was not recoverable from the high-density refractory. The EERC believes that the primary factors contributing to material balances of <100% in the SFS are slag adsorption/absorption into the high-density furnace refractory and unrecovered slag/ash from refractory surfaces.

Fly ash recovered from other system components (drawdown gas line, CAH duct, process air preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping) represented 17% of the theoretical ash for the April test. Nominally, 10% to 15% of the ash in the fuels fired in the SFS has been reaching the baghouse. In April, that value was 9.2% of the total

ash/slag. However, the bags were not removed from the baghouse and thoroughly cleaned following the April test; therefore, the residual dust cake on the bags would definitely increase the baghouse ash to more than 10% of the total.

Figure 3-13 presents a photograph of the slag screen inlet following the April test. This photograph shows that some erosion/corrosion of the slag screen tubes has occurred and refractory aggregate is visible on the tube surfaces. However, the general condition of the tubes following the April test was good, and no modifications or repairs were necessary.

Dilution/Quench Zone

During the January test, slag deposits formed in the vicinity of the FGR nozzles. Because of the slag flow from the slag screen into the dilution/quench zone, it was necessary to clean slag deposits from the area of the FGR nozzles on a periodic basis. However, because of modifications made to the nozzle spool piece (the addition of a water-cooled wall), the slag deposits were more efficiently removed. As a result, cleaning frequency was somewhat variable, about every 2–4 hours.

During the February test, slag deposits formed in the vicinity of the FGR nozzles. However, the deposition was minimal, and no cleaning was required during the 38 hours of coal firing. This result was most likely due to the high collection efficiency of the slag screen and the low ash content and high heating value of the Kentucky bituminous coal.

Figure 3-13. Photograph of slag screen tubes following the April test.

Slag deposits formed near the FGR nozzles during the April test. As a result, it was necessary to clean the area of the FGR nozzles on a periodic basis. The dilution/quench zone was initially cleaned after nearly 43 hours of coal firing. Cleaning frequency was somewhat variable during the balance of the 200-hour test, ranging from 3 to 26 hours, with more frequent cleaning required following the switch to the Illinois No. 6 bituminous coal. About 19% of the ash/slag recovered from the SFS was recovered in the dilution/quench zone. This quantity of material is twice that observed as a result of the January (10%) and February (8%) tests.

Material recovered from the dilution/quench zone as a result of SFS tests prior to 1999 typically represented <13% of the total ash. The larger percentage of total ash showing up in the dilution/quench zone in April is a direct result of reducing the number of tubes in the slag screen from 18 to 9. As previously discussed, reducing the number of tubes in the slag screen was necessary to successfully fire the eastern Kentucky bituminous coal in the SFS. However, as expected, reducing the number of tubes effectively reduced the efficiency of the slag screen, resulting in an increase in the mass of slag/ash recovered from the dilution/quench zone. Downstream of the FGR nozzles, the small quantity of ash observed on the refractory walls was weakly sintered for all three test periods.

Process Air Preheaters

Process air for the CAH tube bank and the RAH panel is heated using air preheater tube bundles located downstream of the CAH. Figures 3-14 through 3-16 summarize process air preheater temperature data as a function of run time for the January, February, and April test

Figure 3-14. Process air preheater temperatures versus run time for the January test, SFS-RH6-0199.

Figure 3-15. Process air preheater temperatures versus run time for the February test, SFS-RH7-0299.

Figure 3-16. Process air preheater temperatures versus run time for the April test, SFS-RH8-0399.

periods, respectively. Further heating of the process air entering the RAH panel was achieved electrically and by recovering heat from the CAH tube bank. Process air for the CAH tube bank is supplied by the first air preheater tube bundle. During the January test, process air entering the CAH tube bank was controlled at set points ranging from 1100° to 1130°F (594° to 610°C) for nominal process air flow rates of 92 to 123 scfm (2.6 to 3.5 m³/min). Process air temperatures at the exits of the other four preheater tube bundles were nominally 1230° to 1320°F (666° to 716°C) for flow rates totaling 100 to 150 scfm (2.8 to 4.2 m³/min). Although the process air preheater heat-transfer rate degraded with time as ash deposits developed on the tube surfaces, process air temperature and flow rate control were adequate to support operation of the CAH tube bank and RAH panel for all three tests.

During the February test, process air entering the CAH tube bank was controlled at set points ranging from 1000° to 1025°F (538° to 552°C) for nominal process air flow rates of 103 to 123 scfm (2.9 to 3.5 m³/min). Process air temperatures at the exits of the other four preheater tube bundles were nominally 1230° to 1320°F (666° to 716°C) for flow rates totaling 100 to 150 scfm (2.8 to 4.2 m³/min).

During the April test, process air entering the CAH tube bank was controlled at set points ranging from 1075° to 1140°F (580° to 616°C) for nominal process air flow rates of 77 to 108 scfm (2.2 to 3.1 m³/min). Process air temperatures at the exits of the other four preheater tube bundles were nominally 1205° to 1320°F (652° to 716°C) for combined flow rates totaling 100 to 150 scfm (2.8 to 4.2 m³/min).

Particulate Emissions

The characteristics of fly ash generated in the high-temperature SFS are different than those observed for a given fuel fired in a conventional pc-fired system. Specific differences observed to date include a reduction in mass loading and particle size. The lower mass loading and smaller particle size were anticipated based on the use of a slag screen at the furnace exit to promote ash collection as slag. Early work with woven glass filter media demonstrated good particulate control. However, on-line cleanability and differential pressure control was inconsistent for most fuel types. Prior to the SFS tests summarized in the report, the original woven glass filter media was replaced with a woven glass/PTFE membrane combination. As a result, on-line cleaning was very effective for the two bituminous coals, and particulate control was as good as, if not better than, observed with the original filter media.

During gas- and coal-fired furnace operation, baghouse temperatures and temperature profiles were nominal, and the electrical heaters worked well, limiting the potential for condensation on start-up and shutdown. Baghouse temperature ranged from 330° to 350°F (166° to 177°C) in January (SFS-RH6-0199); 330° to 340°F (166° to 171°C) in February (SFS-RH7-0299); and from 330° to 367°F (166° to 186°C) in April (SFS-RH8-399).

Flue gas flow rates were 946 to 1046 scfm (26.8 to 29.6 m³/min) in January; 884 to 961 scfm (25.0 to 27.2 m³/min) in February; and 935 to 1030 scfm (26.5 to 29.2 m³/min) in April. Actual flue gas flow rates through the baghouse were 1492 to 1692 acfm (42.2 to 47.9 m³/min) in

January; 1401 to 1535 acfm (39.7 to 43.5 m³/min) in February; and 1420 to 1640 acfm (40.2 to 46.4 m³/min) in April.

The 36 bags (total filtration area of 565 ft² [52.5 m²]) used in the baghouse were a 22-oz/yd² (747 g/m²) woven glass with a PTFE membrane. The filter face velocities when the Illinois No. 6 and Kentucky bituminous coals were fired were 2.4 to 3.0 ft/min (0.74 to 0.91 m/min) and 2.5 to 2.9 ft/min (0.76 to 0.88 m/min), respectively. These filter face velocities are low compared to conventional pulse-jet filtration systems typically operating at or near 4 ft/min (1.2 m/min).

Measured inlet and outlet particulate mass loadings were nominally 0.1003 gr/scf (229.7 mg/Nm³) and 0.0004 gr/scf (0.8015 mg/Nm³), respectively, resulting in a particulate collection efficiency of roughly 99.6% when the Illinois No. 6 bituminous coal was fired in January 1999. The measured inlet particulate loadings are a factor of 20 to 30 less than would be expected in a conventional pc-fired system. This is primarily due to the slag removal in the slag screen, but other contributing factors are slag/ash removal in the dilution/quench zone and downstream heat-transfer surfaces (CAH tubes, process air preheaters, and tube-and-shell heat exchangers). Particulate mass loading at the baghouse inlet was roughly 50% lower than what was measured previously when the Illinois No. 6 bituminous coal was fired in the SFS. One possible explanation for the reduced mass loading at the baghouse inlet is the change in slag screen operating conditions—higher flue gas velocity and differential pressure (the result of the slag damming observed)—which may have increased the slag screen particulate collection efficiency. Also, during SFS shakedown tests, the performance of the slag screen dramatically deteriorated as the uncooled alumina tubes were eroded with time. A higher fly ash mass loading at the inlet to the pulse-jet baghouse was measured as a result. Since early 1998, slag screen performance has improved with water-cooled tubes, although plugging and slag dam problems have been encountered on occasion.

Calculated particulate emissions from the pulse-jet baghouse were 0.0014 lb/MMBtu in January. This is a lower emission rate compared to other SFS tests with Illinois No. 6 bituminous coal (0.0024 to 0.0030 lb/MMBtu). This result is probably best explained by the performance of the new bags with respect to effective on-line cleaning and control of differential pressure.

Measured inlet and outlet particulate mass loadings were nominally 0.0428 gr/scf (98.02 mg/Nm³) and 0.0043 gr/scf (9.8475 mg/Nm³), respectively, resulting in a particulate collection efficiency of roughly 90% when the Kentucky bituminous coal was fired in February. These inlet particulate loadings are a factor of 2 to 5 lower than what was measured previously when the Illinois No. 6 bituminous coal was fired. One contributing factor is the smaller theoretical quantity of ash entering the SFS with the Kentucky fuel for a given firing rate, about 30% of that for the Illinois No. 6 fuel. Calculated particulate emissions from the pulse-jet baghouse were 0.0156 lb/MMBtu. This is an order-of-magnitude increase in particulate emissions compared to the January test and a significantly higher emission rate compared to tests with other coals and lignites (0.0004 to 0.0074 lb/MMBtu). Inspection of the outlet filters resulting from February sampling efforts revealed the presence of ash agglomerates in the center of both filters and no indication of a dust cake. Therefore, the EERC believes that the outlet filters in February

were affected by some degree of acid condensation and/or ash scale/agglomerates dislodging from the surface of flue gas piping downstream from the pulse-jet baghouse.

Measured inlet and outlet particulate mass loadings were nominally 0.0634 gr/scf (145.19 mg/Nm³) and 0.0017 gr/scf (3.8932 mg/Nm³), respectively, resulting in a particulate collection efficiency of roughly 97% when the Kentucky bituminous coal was fired in April. These inlet particulate loadings are still lower than what was measured previously when the Illinois No. 6 bituminous coal was fired and somewhat different when compared to the February Kentucky coal-fired test. The inlet mass loading in April was somewhat higher and probably the result of the limestone fed with the coal in April to modify slag chemistry. The outlet mass loading was a factor of 2.5 lower and is probably a better indication of baghouse performance than the emission rate measured in February. However, the degree of acid condensation has not been determined. Calculated particulate emissions from the pulse-jet baghouse were 0.0068 lb/MMBtu. This is a factor of two reduction in particulate emissions compared to the February test and yet nearly an order-of-magnitude higher emission rate compared to tests with other coals and lignite (0.0004 to 0.0074 lb/MMBtu). Visual inspection of the outlet filters resulting from April sampling did not indicate the presence of ash agglomerates on the filters, and no evidence of a dust cake was noted. Therefore, the EERC believes that the outlet filters in April (when the eastern Kentucky fuel was fired) were affected by acid condensation but to a degree much less significant than observed in February. Evidence of acid condensation was found in the clean air plenum of the pulse-jet baghouse and downstream flue gas piping after the April test. The acid condensation deposits were removed as a function of SFS maintenance.

Sulfur trioxide concentration measurements were made downstream of the pulse-jet baghouse in April. Measurements indicated that when the eastern Kentucky and Illinois No. 6 bituminous coals were fired, the sulfur trioxide concentrations at the pulse-jet baghouse outlet were 3 and 45 ppm, respectively. These values are somewhat consistent with the fuel sulfur content where theoretical sulfur dioxide emissions rates are 1.4 and 6.4 lb/MMBtu, respectively, for the eastern Kentucky and Illinois No. 6 coal. However, firing the Illinois No. 6 coal resulted in a proportionally higher concentration of sulfur trioxide. One possible explanation for the order-of-magnitude difference in measured sulfur trioxide concentrations was the use of limestone addition when the Kentucky coal was fired. Calcium oxide escaping the furnace, slag screen, and dilution/quench zone may have been available to react with the sulfur trioxide when the eastern Kentucky coal was fired. However, baghouse ash analyses do not support this theory since the calcium and sulfur concentrations are as high if not higher for the February test.

In addition to the standard EPA Method 5 sampling completed during the coal-fired test periods, respirable mass emissions (defined below) were measured at the outlet of the pulse-jet baghouse using a TSI Inc. aerodynamic particle sizer (APS-33). This real-time measurement method measures particle mass in the range of 0.5 to 15 μ m. The primary advantages of this system are the high spatial resolution and the short sampling time. In the APS-33, particle-laden air is passed through a thin-walled orifice, with the particles lagging behind the gas because of their higher inertia. The velocity lag is related to the aerodynamic diameter of the particles, allowing the determination of the aerodynamic diameter of a particle by measuring the velocity of a particle as it exits from the orifice. To measure the particle velocity, the APS-33

employs a laser beam split into two beams and refocused onto two rectangular planes a set distance apart in front of the orifice. The light scattered by a particle passing through these beams is collected and focused onto a photomultiplier tube, which emits two pulses separated by the time taken for the particle to cross the distance between the two planes. This time interval is measured electronically and used to calculate the particle's aerodynamic diameter.

Respirable mass is a calculated value defined by the American Council of Governmental and Industrial Hygienists for particles in the size range of 2 to $<10\ \mu\text{m}$ based on aerodynamic diameter. Figure 3-17 presents the respirable mass emissions data for the January (top) and February test (bottom). The data are presented on a mg/m^3 basis versus sampling time. For the Illinois No. 6 coal-fired test in January, the average respirable mass emission rate integrated over 4 hours was $0.0025\ \text{mg}/\text{m}^3$ versus $0.0004\ \text{mg}/\text{m}^3$ for a 2-hour period during the Kentucky coal-fired test in February. For the Illinois No. 6 coal-fired test, individual measurements ranged from 0.0006 to $0.004\ \text{mg}/\text{m}^3$. In February when the Kentucky coal was fired, individual measurements ranged from 0.0001 to $0.0015\ \text{mg}/\text{m}^3$. These data support the probable contamination of the EPA Method 5 outlet filters resulting from sampling in February.

Figure 3-18 presents the respirable mass emissions data for the April test period during Illinois No. 6 coal firing. Data are not available for the eastern Kentucky coal-fired period in April because of an instrument malfunction. The data are presented on a mg/m^3 basis versus sampling time. The average respirable mass emission rate integrated over 2 hours was nominally $0.0024\ \text{mg}/\text{m}^3$, with individual measurements ranging from 0.0006 to $0.05\ \text{mg}/\text{m}^3$. These data are consistent with the January data and indicate that actual particulate emissions were much lower than the mass rates indicated by EPA Method 5 sampling and support the potential contamination of the EPA Method 5 outlet filters by acid condensation in April.

The clean air plenum was removed from the pulse-jet baghouse following each test period. One bag was pulled for inspection following the January test, with multiple bags pulled for inspection following the tests in February and April. Inspection of multiple bags following the February test was deemed necessary because of the higher particulate emissions measured at the outlet of the baghouse as a result of EPA Method 5 sampling. In all three cases, the tube sheet appeared to be very clean, consistent with the low level of particulate emissions generally measured, and the bags pulled for inspection were found to be in good condition. As a result, the bags were not pulled for cleaning after the January, February, or April tests.

After the February and April test periods, some evidence of acid condensation was found in the baghouse clean air plenum and inlet and outlet piping. In addition, inspection of the baghouse outlet piping revealed the presence of some scale-type residue. The residue appeared to be the result of a combination of fine ash particles and acid condensation. The acid condensation most likely occurred during the January test firing the Illinois No. 6 coal, which had a substantially higher sulfur content.

Particle-size analysis was completed for a composite ash sample collected from the baghouse hopper for all three tests. Figure 3-19 summarizes the data and shows the ash to be

Figure 3-17. Respirable mass emission data for the January (top) and February (bottom) tests.

Figure 3-18. Respirable mass emission data for the April test.

Figure 3-19. Baghouse hopper ash particle-size data.

100 wt% <15 μm , 80 wt% <6 μm , and 50 wt% <3 μm for the Illinois No. 6 coal fired in January. However, multicyclone sampling data presented in Figure 3-20 indicated a larger particle size, with only 30 wt% <7 μm .

For the February eastern Kentucky coal test, the baghouse data show the ash to be 100 wt% <10 μm , 80 wt% <5 μm , and 50 wt% <3 μm . In this case, multicyclone data indicated a comparable particle size, 50 wt% <4 μm . The particle-size analysis from the April test with Kentucky coal shows the ash to be significantly larger than in February: 100 wt% <25 μm , 80 wt% <10 μm , and 50 wt% <6 μm . Two possible explanations exist. First, limestone was fed with the coal in April to mitigate plugging problems in the slag screen. In addition, prior to the April test, the slag screen was modified (the number of tubes was reduced from 18 to 9), probably resulting in a decrease in its particle collection efficiency. Multicyclone sampling data in April were consistent with the ash hopper sample data and indicated a comparable particle size with nominally 50 wt% <7.5 μm when either the Kentucky or Illinois No. 6 coal were fired.

Carbon content was also measured in the baghouse ash to determine combustion efficiency. The carbon content of the baghouse ash was found to be 0.50 wt% for the Illinois No. 6 coal fired in January. The baghouse ash carbon content was 0.24 wt% for the eastern Kentucky coal in February, but 0.70 wt% in April. No explanation is available concerning this difference. The high carbon burnout consistently observed in the slagging furnace appears to be primarily a function of the residence time and high operating temperature of the slagging furnace.

Figure 3-20. Multicyclone data resulting from baghouse inlet sampling.

Pulse cleaning of the bags was accomplished on-line using a reservoir pulse-air pressure of nominally 40 psig (2.8 bar) for both fuels. The baghouse differential pressure cleaning set point was 6 in. W.C. (11.2 mmHg). Once the initial dust cake was formed, the cleaning frequency was 4 to 8 hours when the eastern Kentucky coal was fired (with limestone injection to mitigate slag screen plugging) and 3 to 6 hours when the Illinois No. 6 coal was fired (with and without calcium oxide injection to control sulfur trioxide emissions). The bags consistently cleaned to a differential pressure of <2 in. W.C. (<3.7 mmHg). Figure 3-21 presents baghouse differential pressure as function of run time for the April test period.

Carbon Monoxide Emissions

Table 3-6 shows the average gaseous emissions measured during each test. The data are based on furnace exit measurements made in the slag screen outlet. The CO concentration of 40 ppm in February was a direct result of firing the main burner at a low swirl setting resulting in incomplete combustion at the sample point in the slag screen. However, no CO was observed at the baghouse outlet sampling location, indicating that the CO is oxidized in the dilution/quench zone and CAH section. Typical CO concentrations measured in the slag screen were <10 ppm in January and 0 to 40 ppm in February. These CO concentrations are consistent with previous low-swirl burner operating experience when bituminous coal was fired. CO data are not available for the April test at this sample location because of a failed analyzer. However, measurements at the baghouse exit were typically <10 ppm.

Figure 3-21. Baghouse differential pressure versus run time for the April test.

TABLE 3-6

Flue Gas Emissions for Illinois No. 6 and Kentucky Coal-Fired Slagging Furnace Tests		
	Concentration	lb/MMBtu
January (Illinois No. 6 coal)		
O ₂	3.5%–5.0%	
CO ₂	12.9%–13.4%	
CO	<10 ppm	
NO _x	400–600 ppm	0.9–1.4
SO ₂	1800–2800 ppm	6.0–6.5
February (Kentucky coal)		
O ₂	3.5%–4.7%	
CO ₂	12.7%–13.9%	
CO	0–40 ppm	
NO _x	580–725 ppm	1.3–1.5
SO ₂	630–850 ppm	1.0–1.4
April (Kentucky coal)		
O ₂	3.5%–5.0%	
CO ₂	13.2%–14.1%	
CO	Not available	
NO _x	530–630 ppm	0.9–1.1
SO ₂	390–560 ppm	1.2–1.6
April (Illinois coal)		
O ₂	3.2%–4.3%	
CO ₂	13.4%–14.0%	
CO	Not available	
NO _x	460–550 ppm	0.8–1.0
SO ₂	1830–2120 ppm	6.0–6.9

NO_x Emissions

NO_x concentrations in the flue gas ranged from 400 to 725 ppm. Total NO_x emissions (reported as nitrogen dioxide) were determined to range from 0.7 to 1.5 lb/MMBtu. NO_x emissions were higher during individual test periods, represented by higher average coal feed rates. Also, NO_x emissions were marginally higher when the eastern Kentucky fuel was fired compared to the Illinois No. 6 fuel. The auxiliary burner firing condition is also believed to have affected the NO_x concentrations and emissions; however, no specific tests have been conducted to document the effect of the auxiliary burner on NO_x emissions.

SO₂ Emissions

No attempt at controlling sulfur emissions was made. Calculated maximum theoretical sulfur dioxide emissions were 13.5 to 14.6 lb/hr (6.1 to 6.6 kg/hr) or 6.5 lb/MMBtu for the Illinois No. 6 coal in January; 3.1 to 3.8 lb/hr (1.4 to 1.7 kg/hr) or 1.4 lb/MMBtu for the Kentucky coal in February; 2.9 to 3.5 lb/hr (1.3 to 1.6 kg/hr) or 1.4 lb/MMBtu for the eastern

Kentucky coal in April and 11.8 to 17.2 lb/hr (5.4 to 7.8 kg/hr) or 6.4 lb/MMBtu for the Illinois No. 6 coal in April. These rates are based on the main burner firing rate and the sulfur content and heating value of the fuel determined for the composite fuel samples analyzed. Sulfur dioxide emissions for the eastern Kentucky coal, calculated based on measured sulfur dioxide in the flue gas, flue gas flow rate, and the coal-firing rate, resulted in values ranging from 1.2 to 1.6 lb/MMBtu. The most likely explanation for the difference in calculated maximum sulfur dioxide emission rates, 1.4 versus 1.6 lb/MMBtu, is that the composite fuel sample did not adequately represent fuel sulfur spikes documented by the flue gas sulfur dioxide analyzer.

3.1.2 CAH Tube Bank Performance

CAH tube bank performance met all test objectives relative to heat transfer and its support of the RAH panel. Performance differences relative to fuel ash properties were as expected. The only issue not adequately addressed to date is the potential effectiveness of sootblowing. Sootblowing of the CAH tube bank will be addressed in future SFS tests within the Combustion 2000 Program.

The CAH tube bank was installed and initially evaluated during a shakedown test completed in October 1997. Process air flow was adequate for temperature control and to evaluate the performance of the CAH tube bank during the tests performed in January, February, and April 1999. Figures 3-22 through 3-24 summarize CAH tube bank surface and flue gas temperatures, process air temperatures, and process air flow rate data for the January test (SFS-

Figure 3-22. CAH tube surface and flue gas temperatures versus run time for the January test, SFS-RH6-0199.

Figure 3-23. CAH process air temperatures versus run time for the January test, SFS-RH6-0199.

Figure 3-24. CAH process air, RAH process air, quench gas, and flue gas flow rates versus run time for the January test, SFS-RH6-0199.

RH6-0199). Figure 3-25 illustrates the location of thermocouples in the CAH tube bank, and Table 3-7 presents a list of thermocouple descriptions.

Prior to an August 1998 test, all of the CAH thermocouples were replaced or repaired in conjunction with the installation of fins on the air-cooled tubes. However, one tube surface thermocouple (CAHIT3) was damaged when the tube bank was installed in the flue gas duct. One additional CAH thermocouple failed during both an August and December 1998 test, and a fourth thermocouple failed at the beginning of the January test. Therefore, during the three tests discussed in this report, one of the five surface thermocouples was functioning properly.

Based on the single thermocouple measurement, the clean tube surface temperatures were nominally 1565°F (852°C) with the surface temperature decreasing to 1340°F (982°C) as ash deposits developed and adjustments were made to the process air flow rate. While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 44,000 Btu/hr (46,420 kJ/hr). This result was observed for the following conditions:

- Process air flow rate of 138 scfm (3.9 m³/min)
- Inlet process air temperature of 1080°F (582°C)
- Outlet process air temperature of 1240°F (671°C)

Figure 3-25. Thermocouple locations in the CAH tube bank.

TABLE 3-7

Description of CAH Thermocouple Locations ¹			
Category	No.	Label	Description
Air Inlet	1	CAHTC1	Bulk flow entering the inlet header
	2	CAHTC2	Air entering center tube
	3	CAHTC3	Air entering most downstream tube
Air Outlet	4	CAHTC6	Air leaving center tube
	5	CAHTC7	Air leaving most downstream tube
	6	CAHTC5	Air leaving most upstream tube
	7	CAHTC8	Air leaving side tube
Air in Active Region	8	CAHTC10	Bottom of center tube
	9	CAHTC11	4 in. up outside annulus, center tube
	10	CAHTC9	8 in. up outside annulus, center tube
Tube Surface	11	CAHIT1	1 in. up center tube, facing upstream (failed)
	12	CAHIT2	5 in. up center tube, facing upstream
	13	CAHIT3	8 in. up center tube, facing upstream (failed)
	14	CAHIT4	5 in. up center tube, facing to side (failed)
	15	CAHIT5	5 in. up center tube, facing downstream (failed)
Header Shell	16	CAHTC4	Next to shell on outside, between return air pipes (failed)

¹ Thermocouple locations are illustrated in Figure 3-25.

- Flue gas temperature of 1800°F (982°C) entering the CAH tube bank.

Figure 3-26 presents heat recovery in the CAH as a function of run time for the January test.

When coal firing (Illinois No. 6) began, surface temperatures initially decreased at a rate of nominally 5°F/hr (3°C/hr) over nearly 20 hours as ash deposits developed on the surface of the tubes. After nearly 40 hours of coal firing, there was no further decrease in tube surface temperature. It must be noted that process air flow rates were also decreasing (0.01 scfm/0.0003 m³/min) over these time frames in an attempt to maintain a relatively constant process air exit temperature. The minimum process air flow rate through the CAH tube bank was 92 scfm (2.6 m³/min). As ash deposits developed on the tube surfaces, heat recovery from the CAH tube bank decreased from roughly 44,060 Btu/hr (46,483 kJ/hr) to 17,625 Btu/hr (18,594 kJ/hr). Heat recovery from the CAH tube bank remained at this level for nearly 17 hours of coal firing prior to the termination of the coal feed. These data are consistent with previous results observed when Illinois No. 6 coal was fired.

Figure 3-26. CAH heat recovery versus run time for the January test, SFS-RH6-0199.

On the basis of these data, it appears that the addition of the fins to the air-cooled tubes improved heat recovery during the coal-fired test period. The fins appear to have reduced the rate of heat-transfer degradation as ash deposits developed and helped to maintain a higher heat-transfer rate once the deposits had formed. However, no improvement in heat recovery was observed during the initial natural gas-fired period with clean tube surfaces compared to previous test periods.

EERC personnel did not clean the CAH tube bank during the January test in order to facilitate the development of ash deposits for characterization. CAH tube bank plugging was not a problem. No deposits were observed bridging the flue gas paths between the tubes. The deposits that formed were limited to the leading and trailing edges of the tubes. However, these deposits did bridge the area between the tubes in the direction of the flue gas flow.

Figure 3-27 presents a photograph of ash deposits on the surface of the tubes following the January test. The photograph shows three of the five uncooled tubes as well as two of the seven air-cooled finned tubes. The leading- and trailing-edge deposits are readily visible, with bare metal surfaces visible on the back half of the uncooled tubes. The pieces of tube deposit missing from the photograph of the air-cooled tubes fell off as the tube bank was removed from the duct.

Deposit strength is a function of ash chemistry, particle size, and temperature history. The relative strength of the deposits was indicated by the fact that the deposits generally remained intact when the CAH tube bank was removed from the duct. Also, the deposits were generally

Figure 3-27. Photograph of ash deposits on the CAH tubes following the January test firing Illinois No. 6 bituminous coal.

removed intact from the tube surfaces. The total weight of the deposits collected from the CAH tubes and duct was 14 lb (6.4 kg). The total weight of the deposits collected from the CAH tubes was 4 lb (1.8 kg). On a mass per unit time basis, the ash deposition rate for this Illinois No. 6 coal-fired test would be 0.07 lb/hr (30.3 g/hr) of coal firing. Incorporating the surface area of the tube bank (6.28 ft² or 0.58 m²) results in a value of 0.01 lb/hr-ft² (52.2 g/hr-m²). On a coal-firing-rate basis, the CAH ash deposition rate would be 0.03 lb/MMBtu (13.3 g/10⁶ kJ). These calculated values are comparable to previous Illinois No. 6 tests.

Figures 3-28 through 3-30 summarize CAH tube bank surface and flue gas temperatures, process air temperatures, and process air flow rate data for the February test (SFS-RH7-0299). While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 44,474 Btu/hr (46,921 kJ/hr). This result was observed for the following conditions:

- Process air flow rate of 127 scfm (3.6 m³/min)
- Inlet process air temperature of 1010°F (544°C)
- Outlet process air temperature of 1195°F (646°C)
- Flue gas temperature of 1800°F (982°C) entering the CAH tube bank.

Figure 3-31 presents heat recovery in the CAH as a function of run time for the February test.

Figure 3-28. CAH tube surface and flue gas temperatures versus run time for the February test, SFS-RH7-0299.

Figure 3-29. CAH process air temperatures versus run time for the February test, SFS-RH7-0299.

Figure 3-30. CAH process air, RAH process air, quench gas, and flue gas flow rates versus run time for the February test, SFS-RH7-0299.

Figure 3-31. CAH heat recovery versus run time for the February test, SFS-RH7-0299.

When coal firing (Kentucky) began, surface temperatures initially decreased at a rate of nominally 5°F/hr (3°C/hr) over nearly 12 hours as ash deposits developed on the surface of the tubes. After nearly 40 hours of coal firing, there was no further decrease in tube surface temperature. It must be noted that process air flow rates were also decreasing (0.01 scfm/0.0003 m³/min) over these time frames in an attempt to maintain a relatively constant process air exit temperature. The minimum process air flow rate through the CAH tube bank was 104 scfm (2.9 m³/min). As ash deposits developed on the tube surfaces, heat recovery from the CAH tube bank decreased from roughly 46,500 Btu/hr (49,058 kJ/hr) to 27,000 Btu/hr (28,485 kJ/hr). The coal feed was terminated at this time because of the plugging problems in the slag screen. When coal feed resumed, heat recovery from the CAH tube bank was nominally 30,000 Btu/hr (31,650 kJ/hr). Heat recovery decreased to nominally 29,000 Btu/hr (30,595 kJ/hr) over the final 2.5 hours of coal firing prior to the termination of the coal feed. These data indicate that heat recovery from the CAH tube bank when the Kentucky bituminous coal was fired is significantly greater as compared to the Illinois No. 6 coal data. This result is most likely due to the smaller quantity of ash in the Kentucky fuel and the differences in ash properties.

EERC personnel did not clean the CAH tube bank during the February test in order to facilitate the development of ash deposits for characterization. CAH tube bank plugging was not a problem. No deposits were observed bridging the flue gas paths between the tubes. The deposits that formed were limited to the leading and trailing edges of the tubes. In addition, these deposits did not bridge the area between the tubes in the direction of the flue gas flow as was observed when the Illinois No. 6 coal was fired.

Figure 3-32 presents a photograph of ash deposits on the surface of the tubes following the February test. The photograph shows three of the five uncooled tubes as well as two of the seven air-cooled finned tubes. The leading- and trailing-edge deposits are readily visible, with very little ash present on the side walls of either the uncooled or cooled metal surfaces. There do not appear to be any pieces of tube deposit missing in the photograph.

Deposit strength is a function of ash chemistry, particle size, and temperature history. The deposits remained intact when the CAH tube bank was removed from the duct. However, the small quantity of deposit and, therefore, minimal weight may have been the primary reason the deposit remained intact when the tube bank was removed from the duct. Also, the deposits from the cooled tubes were not generally removed intact from the tube surfaces. The total weight of the deposits collected from the CAH tubes and duct was 2.2 lb (1.0 kg). The total weight of the deposits collected from the CAH tubes was 1 lb (0.5 kg). On a mass per unit time basis, the ash deposition rate for this Kentucky coal-fired test would be 0.03 lb/hr (13.6 g/hr) of coal firing. Incorporating the surface area of the tube bank (6.28 ft² or 0.58 m²) results in a value of 0.005 lb/hr-ft² (23.4 g/hr-m²). On a coal-firing-rate basis, the CAH ash deposition rate would be 0.01 lb/MMBtu (5.9 g/10⁶ kJ). These calculated values are nominally a factor of 3 smaller than those observed for the Illinois No. 6 coal, consistent with the Kentucky coal's lower ash content and higher heating value.

Table 3-8 shows the compositions of the deposits that formed on both the uncooled dummy tubes and the cooled tubes during the February test. The compositions show that, like the slag

Figure 3-32. Photograph of ash deposits on the CAH tubes following the February test firing eastern Kentucky bituminous coal.

TABLE 3-8

CAH Deposit Samples from the February Test					
Oxides, ¹ wt%	Kentucky Coal	Uncooled Front	Uncooled Back	Cooled Front	Cooled Back
SiO ₂	40.4	53.5	52.1	53.2	53.2
Al ₂ O ₃	30.8	20.1	20.7	20.7	20.6
Fe ₂ O ₃	10.6	14.1	14.2	14.5	14.1
TiO ₂	1.1	1.2	1.3	1.3	1.3
P ₂ O ₅	0.1	0.2	0.4	0.3	0.3
CaO	10.9	4.4	2.4	3.3	2.4
MgO	2.3	1.8	1.8	1.8	1.9
Na ₂ O	1.5	1.8	3.0	1.8	2.5
K ₂ O	2.3	2.8	4.2	3.1	3.8
SO ₃ ²	6.7	0.3	0.2	1.0	0.4

¹ Oxide concentrations normalized to an SO₃-free basis.

² SO₃ concentrations normalized with other oxides.

collected in the slag screen, the deposits are dominated by larger particles enriched in silica and iron and depleted in alumina and calcia. It is unusual that the compositions of the upstream and downstream deposits are so similar, since the upstream deposits are usually more enriched with

larger particles and the downstream deposits usually more enriched with smaller particles. SEM analyses showed that essentially all of the different deposits were composed of complex silicates, except for a thin powder layer adjacent to the tube, which contained approximately 15% sulfate material.

Figures 3-33 through 3-35 summarize CAH tube bank surface and flue gas temperatures, process air temperatures, and process air flow rate data for the April test (SFS-RH8-0399). While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 40,000 Btu/hr (42,200 kJ/hr). This result was observed for the following conditions:

- Process air flow rate of 111 scfm (3.1 m³/min)
- Inlet process air temperature of 1080°F (582°C)
- Outlet process air temperature of 1270°F (688°C)
- Flue gas temperature of 1790°F (977°C) entering the CAH tube bank.

Figure 3-36 presents heat recovery in the CAH as a function of run time for the April test.

When coal firing (eastern Kentucky) began, surface temperatures initially decreased at a rate of nominally 5°F/hr (3°C/hr) over nearly 10 hours as ash deposits developed on the surface of the tubes. After 40 hours of coal firing, the rate of decrease was 0.7°F/hr (0.4°C/hr). No

Figure 3-33. CAH tube surface and flue gas temperatures versus run time for the April test, SFS-RH8-0399.

Figure 3-34. CAH process air temperatures versus run time for the April test, SFS-RH8-0399.

Figure 3-35. CAH process air, RAH process air, quench gas, and flue gas flow rates versus run time for the April test, SFS-RH8-0399.

Figure 3-36. CAH heat recovery versus run time for the April test, SFS-RH8-0399.

further decrease in tube surface temperature was noted, other than changes related to flue gas flow rates, flue gas temperatures, process air flow rates, and process air temperatures, until the eastern Kentucky coal was replaced by the Illinois No. 6 coal. It must be noted that process air flow rates were also decreasing ($0.1 \text{ scfm}/0.003 \text{ m}^3/\text{hr}$) over these time frames in an attempt to maintain a relatively constant process air exit temperature. The minimum process air flow rate through the CAH tube bank was 77 scfm ($2.2 \text{ m}^3/\text{min}$). As ash deposits developed on the tube surfaces, heat recovery from the CAH tube bank decreased from roughly $40,000 \text{ Btu/hr}$ ($42,200 \text{ kJ/hr}$) to $21,200 \text{ Btu/hr}$ ($22,366 \text{ kJ/hr}$) when the eastern Kentucky coal was fired. Heat recovery from the CAH tube bank remained at this level for nearly 42 hours prior to the switch to the Illinois No. 6 coal. One reason for the steady heat recovery rate may have been spontaneous shedding of the ash-fouling deposits from the CAH tubes, as indicated by piles of ash at the bottom of the tubes. As shown in Table 3-8, the CAH deposits formed when the eastern Kentucky coal was fired contained around 50% silica, and all alkali and alkaline-earth species were present in very low concentrations, so limited sintering at the temperatures of the CAH would be expected.

Over the final 51 hours of coal firing (Illinois No. 6), the heat recovery from the CAH tube bank decreased and eventually stabilized at $16,000 \text{ Btu/hr}$ ($16,880 \text{ kJ/hr}$) prior to termination of the coal feed. These data are generally consistent with the February test firing eastern Kentucky coal as well as previous tests firing Illinois No. 6 coal. A comparison of the results shows a nominal 30% higher heat recovery rate in the CAH tube bank when the eastern Kentucky coal is fired, probably because of spontaneous ash deposit shedding. However, these data do not address

the potential for improved heat recovery for either fuel type as a function of an effective sootblowing system.

These data continue to support the conclusion that the addition of the fins to the air-cooled tubes improves heat recovery during the coal-fired test periods. The fins appear to reduce the rate of heat-transfer degradation as ash deposits developed and help to maintain a higher heat-transfer rate once the deposits have formed. However, no improvement in heat recovery is observed during the initial natural gas-fired periods with clean tube surfaces.

EERC personnel did not clean the CAH tube bank during the April test, and ash deposits were not characterized as a result of the need to switch fuels during the 200-hour test. CAH tube bank plugging was not a problem. No deposits were observed bridging the flue gas paths between the tubes. The deposits that formed were limited to the leading and trailing edges of the tubes. However, these deposits did bridge the area between the tubes in the direction of the flue gas flow. Deposit bridging between tubes in the direction of the flue gas flow may have been the result of a longer eastern Kentucky coal-fired period or occurred as a result of firing the Illinois No. 6 coal during the last 51 hours. EERC personnel believe the latter scenario more likely. Future SFS tests should answer this question.

Figure 3-37 presents a photograph of ash deposits on the surface of the tubes following the April test. The photograph shows three of the five uncooled tubes as well as two of the seven air-cooled finned tubes. The leading- and trailing-edge deposits are readily visible, with bare metal surfaces visible on the back half of the uncooled tubes. The pieces of tube deposit missing from

Figure 3-37. Photograph of ash deposits on the CAH tubes following the April test firing eastern Kentucky and Illinois No. 6 bituminous coal.

the photograph of the air-cooled tubes fell off as the tube bank was removed from the duct. Because two different fuels were fired during this test, a discussion of deposit strength, weight, and deposition rate is not warranted.

3.1.3 RAH Panel Performance

RAH panel performance was excellent during the test periods completed in support of this project. Heat transfer was better than previously observed. No ceramic tile failures occurred, although tile cracking occurred as a result of thermal cycles. Process air temperatures of 1625° to 1800°F were achieved and controlled at the RAH exit based on process air flow rate.

Initial shakedown and testing of the RAH panel took place in December 1997. Testing of the RAH panel continued in January, February, and April 1999 following its reassembly in early January. Reassembly of the RAH panel was necessary because of ceramic tile failures in August 1998. The primary purpose of the January, February, and April tests was to further evaluate the RAH panel performance relative to heat transfer, tile and tube temperatures, and process air temperatures and flow rates. In addition, a critical aspect of RAH panel performance is the ability of the ceramic tiles to withstand the slag attack and thermal cycling conditions in the slagging furnace. Generally, the performance of the RAH panel during the three test periods discussed in this report was as anticipated, with no significant process or material problems observed.

The RAH panel ceramic tiles were thoroughly inspected upon initial installation and following each week of operation. The initial inspection revealed the presence of minor cracks in two of the five ceramic tiles. Cracks were not visible in either of the top or bottom support blocks. Figure 3-38 is a photograph of the new ceramic tiles installed on the RAH panel inside of the slagging furnace prior to the January 1999 test. The cracks visible at the time were hairline cracks in the large upper and lower tiles. The large upper tile had five visible cracks originating from the left edge and one crack originating from the top edge. Cracks originating from the left edge were about 0.75 in. (1.9 cm) in length and are not visible in the photograph. The vertical crack is visible in the photograph as a result of the application of a blue die. In addition, rough surface pitting of the tile is evident at the end of the vertical crack in the upper center of the tile. The large lower tile had one crack originating on the left edge and a few rough surface pits along the right edge near the middle of the tile. Neither the crack nor the surface pits in the large lower tile are visible in the photograph.

The cracks found in new tiles are believed to result from stresses encountered during tile fabrication, the actual casting/cooling process, and the machining of the tiles. These stresses and the resulting cracks could be reduced if the tiles could be formed in near net shapes, eliminating the need for machining. Work in this area is progressing within the Combustion 2000 HiPPS program.

Figure 3-39 presents photographs of the furnace interior after the January (top) and February (bottom) tests. Both photographs illustrate the excellent condition of the high-density furnace refractory as well as the darkening of the refractory with exposure to slag as a result of coal firing. Exposure of the RAH ceramic tiles to slag during coal firing in January darkened the

Figure 3-38. Photograph of new ceramic tiles installed on the RAH panel inside of the slagging furnace in January 1999.

tiles as a result of the residual slag layer on the surface. No additional tile color change is evident following the February test. Although not obvious in the photos, the slag layer on the tiles is thin and appears to be uniform with no evidence of any extensive slag buildup. While there was some slag present in the seams between the tiles, there was no evidence of any fusion between adjacent tiles. Therefore, the 4-hour period of natural gas firing prior to SFS cooldown appears to be adequate to prevent buildup of excess slag on the surface of the tiles or in the seams between tiles for the Illinois No. 6 and Kentucky bituminous coals. Also, any quantity of slag present in the seams between tiles appears to crack as a result of cooldown and tile movement.

Figure 3-40 presents a photograph of the furnace interior after the April test and illustrates the good condition of the high-density furnace refractory as well as the darkening of the refractory with exposure to slag. With each week of coal firing, the high-density furnace refractory gets darker. The high-density refractory immediately below the RAH panel is showing signs of deterioration as a result of slag dripping off the bottom RAH support brick onto the refractory.

Figure 3-41 illustrates the visible cracks found in the RAH tiles following the January (left) and February (right) tests. Overall, the tiles appear to be in good condition. Following the January test, visible cracks were only evident in two tiles, the small and large upper tiles. The small crack evident in the large lower tile prior to coal firing was covered with slag and was not evident following the January test. One crack was evident in the small upper tile following the January test. The crack originated on the left edge and was <3 in. (<7.6 cm) in length. Six cracks

Figure 3-39. Photographs of the RAH panel inside of the slagging furnace following the January (top) and February (bottom) tests.

Figure 3-40. Photograph of the RAH panel inside of the slagging furnace following the April test.

Figure 3-41. Illustrations of cracks found in the ceramic tiles/bricks of the RAH panel after testing in January (left) and February (right) 1999.

were visible in the large upper tile following the January test, four originating from the left edge, one from the top edge, and one originating from the area of the rough surface pits and extending down toward the right edge. The four cracks originating from the left edge were visible prior to exposure of the tile to furnace conditions. However, one of the cracks had grown in length and intersected the vertical crack originating from the top edge. A fifth crack that had been observed originating from the left edge prior to tile exposure to furnace conditions was not evident after the January and February tests as a result of slag covering the tile. The vertical crack in the large upper tile does not appear to have changed as a result of the January and February tests. However, the combination of the vertical crack, the crack extending from the left edge, and the new crack extending toward the right edge could be problematic with further heating and cooling cycles. The only other change in tile cracking that was observed following the February test was the appearance of a new crack originating on the lower right edge of the small upper tile.

Figure 3-42 illustrates the visible cracks found in the RAH tiles following the April test. Overall, the condition of the tiles deteriorated somewhat with each test, with the small lower tile showing the greatest degree of erosion/corrosion. This is believed to result from the combination of its higher surface temperature and the greater quantity of slag flowing over its surface relative to the other tiles. The surface temperature of the small lower tile, although not measured, is believed to be higher than the three larger tiles because the backside of this tile is insulated within the radiation cavity and is not directly cooled by the heat-transfer surfaces. The greatest quantity of slag also flows over this tile because of its location below the other tiles.

Figure 3-42. Illustration of cracks found in the ceramic tiles/bricks of the RAH panel after testing in April 1999.

The cracks in the large lower and middle tiles were hairline cracks posing no concern following the April test. The large upper tile had the most extensive cracking and, therefore, poses a concern with respect to potential failure. The five cracks originating from the left edge were visible prior to exposure of the tile to furnace conditions, although one of the cracks has grown in length and intersects the vertical crack originating from the top edge. The vertical crack in the large upper tile does not appear to have changed as a result of the April test. However, the combination of cracks in the large upper tile could be problematic with further heating and cooling cycles.

Heatup/cooldown cycles are believed to be the primary cause of RAH panel ceramic tile/brick cracking and the propagation of cracks formed during tile fabrication, with slag contributing to erosion/corrosion of surfaces and imparting stresses on the ceramic tile as it finds its way into seams between tiles. Figure 3-43 is a photograph of the lower support brick, small lower tile, and the lower edge of the large lower tile following the February test. Figure 3-44 presents a photograph of the RAH panel from inside of the furnace following the April test. Both photographs show where the flow of slag has caused erosion/corrosion of the tile surfaces. This observation is consistent with those made concerning the original RAH tiles installed in December 1997 and removed subsequent to failure in August 1998. In addition, the photographs illustrate the small quantity of slag found in the seams between the tiles.

Figures 3-45 through 3-47 summarize the RAH ceramic tile temperatures, tube surface temperatures, and process air temperatures for the January test (SFS-RH6-0199). The process air flow rate data for the RAH panel were summarized in Figure 3-24. Figure 3-48 illustrates the

Figure 3-43. Photograph of the RAH lower support brick, small lower tile, and the lower edge of the large lower tile following the February test.

Figure 3-44. Photograph of the RAH panel from inside of the furnace following the April test.

Figure 3-45. RAH ceramic tile temperatures versus run time for the January test, SFS-RH6-0199.

Figure 3-46. RAH tube surface temperatures versus run time for the January test, SFS-RH6-0199.

Figure 3-47. RAH process air temperatures versus run time for the January test, SFS-RH6-0199.

Figure 3-48. Thermocouple locations in the RAH Panel.

location of thermocouples in the RAH panel, and Table 3-9 describes the RAH thermocouples. The indicated ceramic tile surface temperatures (cavity-side) ranged from nominally 2040° to 2205°F (1116° to 1208°C), based on measurements made at the center of each of the three large tiles once the SFS had stabilized thermally (Run Hours 45 through 99). Higher tile surface temperatures (furnace-side), 2620° to 2693°F (1438° to 1479°C), were measured near the center of the large middle tile. Tile surface temperatures during the January test were somewhat higher yet comparable to the temperatures observed during the first RAH coal-fired test completed in December 1997. However, the furnace-side tile temperature is a new thermocouple location. Therefore, a direct comparison with previous data is not appropriate.

RAH process air flow rates during the January test were controlled at 150, 180, 200, 205, and 220 scfm (4.2, 5.1, 5.7, 5.8, and 6.2 m³/min), with 200 scfm (5.7 m³/min) used primarily. Changes in process air flow rates had a definite effect on indicated tile surface temperatures. As process air flow rates were reduced, tile surface temperature increased. Subsequently, when process air flow rates were increased, tile surface temperatures decreased. This effect is most evident for process air flow rate changes at Run Hours 68, 79, 90, and 93.

RAH tube surface temperatures ranged from nominally 1330° to 1970°F (721° to 1077°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates had noticeable effects on all tube surface temperatures. Tube surface temperature step changes were most noticeable for surface temperature measurements near the process air exit and on the front side of the tubes.

TABLE 3-9

Description of RAH Panel Thermocouple Locations ¹			
Category	No.	Label	Description
Air Inlet	1	HP Air In	Provided by the EERC, in pipe before inlet header
	2	RAHT11	Air entering RAH through center tube
Air Outlet	3	RAHT18	Air leaving left (south) tube
	4	RAHT9	Air leaving middle tube
	5	RAHT12	Air leaving right (north) tube
MA Tube Surface	6	RAHT1	Top of middle tube facing cold side
	7	RAHT2	Middle of middle tube facing other tube
	8	RAHT3	Top of middle tube facing toward furnace
	9	RAHT4	Middle of middle tube facing cold side
	10	RAHT5	Middle of middle tube facing toward furnace
	11	RAHT6	Bottom of middle tube facing cold side
	12	RAHT7	Removed
	13	RAHT8	Removed
	14	RAHT10	Bottom of the middle tube facing toward furnace
	15	RAHT13	Removed
	16	RAHT14	Top of north tube facing toward furnace
	17	RAHT15	Bottom of north tube facing toward furnace
	18	RAHT16	Removed
	19	RAHT17	Bottom of north tube facing toward side wall
	20	RAHT28	Top of south tube facing toward furnace
	21	RAHT29	Bottom of south tube facing toward furnace
Inner Surface of Monofrax bricks	22	RAHT19	Top tile, center
	23	RAHT20	Removed
	24	RAHT21	Removed
	25	RAHT22	Middle tile, center
	26	RAHT23	Middle tile, right center hot-side surface
	27	RAHT24	Middle tile, left side rail
	28	RAHT27	Removed
	29	RAHT25	Lower tile, center
	30	RAHT26	Removed

¹ Thermocouple locations are illustrated in Figure 3-48.

Tube surface temperatures in January were comparable to all previous bituminous coal-fired tests.

Heat recovery data from the RAH panel are presented in Figure 3-49 for the January test. At process air flow rates of 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m³/min), the heat recovered from the RAH panel during coal firing was 120,000 Btu/hr (126,600 kJ/hr), 125,960 to 136,540 Btu/hr (132,888 to 144,050 kJ/hr), and 128,850 to 144,230 Btu/hr (135,937 to 152,163 kJ/hr), respectively. For process air flow rates of 180 and 200 scfm (5.1 and 5.7 m³/min),

Figure 3-49. RAH heat recovery versus run time for the January test, SFS-RH6-0199.

the heat recovery ranges are a function of minor adjustments to the coal feed rate, combustion air flow rates, and main burner swirl setting. The main burner firing rate was nominally 2.1 to 2.25 MMBtu/hr (2.2 to 2.3×10^6 kJ/hr).

A comparison of the RAH panel data for the January Illinois No. 6 bituminous coal-fired test and the previous tests firing the same fuel indicates that there has been a significant improvement in the heat recovery rate. During previous test periods, the heat recovery rate in the RAH panel was $<120,000$ Btu/hr ($<126,600$ kJ/hr). However, in January, the heat recovery rate was generally $>120,000$ Btu/hr ($>126,600$ kJ/hr). The higher heat recovery rate observed in January was potentially a function of many factors: 1) the SRAH panel was no longer in place, 2) a minimal main burner swirl setting resulted in a more uniform temperature over the length of the furnace, 3) the total furnace firing rate was somewhat higher in January than tests completed in late 1997 and early 1998, and 4) the new condition of the high-density refractory may have resulted in a slight reduction in furnace heat loss. Another possible contributing factor may have been the position of the inlet and outlet process air thermocouples. These thermocouples were reinstalled in January when the RAH panel was reassembled. Although every effort was made to place the thermocouples in exactly the same position they had previously occupied, it is possible that the measurement location was altered slightly. Further testing and data review would be necessary to develop an explanation for the higher RAH heat recovery observed in January.

Figures 3-50 through 3-52 summarize the RAH ceramic tile temperatures, tube surface temperatures, and process air temperatures for the February test (SFS-RH7-0299). The process air flow rate data for the RAH panel were summarized in Figure 3-30. Once the SFS had

Figure 3-50. RAH ceramic tile temperatures versus run time for the February test, SFS-RH7-0299.

Figure 3-51. RAH tube surface temperatures versus run time for the February test, SFS-RH7-0299.

Figure 3-52. RAH process air temperatures versus run time for the February test, SFS-RH7-0299.

stabilized thermally (Run Hours 35 through 65 and 80 through 82), the indicated ceramic tile surface temperatures (cavity side) ranged from nominally 2070° to 2170°F (1133° to 1188°C), on the basis of measurements made at the center of each of the three large tiles. Higher tile surface temperatures (furnace-side), 2640° to 2690°F (1449° to 1477°C), were measured near the center of the large middle tile. Tile surface temperatures during the February test were comparable to those observed in January.

RAH process air flow rates during the February test were controlled at 180 and 200 scfm (5.1 and 5.7 m³/min), with 200 scfm (5.7 m³/min) used primarily. Changes in process air flow rates had a definite effect on indicated tile surface temperatures as observed for the January test. This effect is evident for process air flow rate changes at Run Hours 51 and 55.

RAH tube surface temperatures ranged from nominally 1370° to 1980°F (744° to 1083°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates had noticeable effects on all tube surface temperatures. Tube surface temperature step changes were most noticeable for surface temperature measurements near the process air exit and on the front side of the tubes. Tube surface temperatures in February were comparable to all previous bituminous coal-fired tests, yet somewhat higher (10° to 40°F/6° to 22°C) than the temperatures observed in January.

Process air inlet temperature ranged from 1140° to 1190°F (616° to 644°C) but was nominally 1170° to 1190°F (633° to 666°C) for most of the coal-fired operational period. Outlet process air temperatures ranged from nominally 1650° to 1790°F (899° to 977°C). The effect of process air flow rate can be seen in the process air outlet temperature data. As process air flow rate decreases, process air exit temperature increases, as expected. These process air flow rate changes are noted at Run Hours 51 and 55. At Run Hours 34 and 41, a step increase in the process air inlet temperature results in a comparable increase in the process air outlet temperatures for a process air flow rate of 200 scfm (5.7 m³/min).

Heat recovery data from the RAH panel are presented in Figure 3-53 for the February test. At process air flow rates of 180 and 200 scfm (5.1 and 5.7 m³/min), the heat recovered from the RAH panel during coal firing was 131,730 to 134,615 Btu/hr (138,975 to 142,019 kJ/hr) and 132,690 to 140,385 Btu/hr (139,988 to 148,106 kJ/hr), respectively. For process air flow rates of 180 and 200 scfm (5.1 and 5.7 m³/min), the heat recovery ranges are a function of minor adjustments to the coal feed rate and combustion air flow rates. The main burner firing rate was nominally 2.1 to 2.3 MMBtu/hr (2.2 to 2.3 × 10⁶ kJ/hr).

A comparison of the RAH panel data for the February Kentucky bituminous coal-fired test and the January test firing Illinois No. 6 bituminous coal indicates a similar heat recovery rate. Although the low end of the ranges were higher during the February test. Again, these heat recovery rates are higher compared to bituminous coal-fired test periods in 1997 and 1998 where heat recovery rates in the RAH panel were typically <120,000 Btu/hr (<126,600 kJ/hr). As

Figure 3-53. RAH heat recovery versus run time for the February test, SFS-RH7-0299.

previously stated in reference to the January data, the higher heat recovery rate observed in February was probably a function of many factors.

Figures 3-54 through 3-56 summarize the RAH ceramic tile temperatures, tube surface temperatures, and process air temperatures for the April test (SFS-RH8-0399). The process air flow rate data for the RAH panel were summarized in Figure 3-35. The indicated ceramic tile surface temperatures (cavity-side) ranged from nominally 2000° to 2140°F (1094° to 1171°C), based on measurements made at the center of each of the three large tiles once the SFS had stabilized thermally (Run Hours 50 through 248). Higher tile surface temperatures (furnace-side), 2400° to 2630°F (1316° to 1444°C), were measured near the center of the large middle tile. Tile surface temperatures during the April test were somewhat lower than the temperatures observed during the RAH coal-fired tests in January and February. Also, there is no obvious explanation for the drop in the furnace-side tile surface temperature that occurred just prior to Run Hour 100. One possibility is the degradation of the thermocouple junction as a result of slag erosion/corrosion of the tile surface. The thermocouple must be effectively attached and measuring a relative furnace-side temperature or the reading would have decreased to a value at or below the values indicated by TC19, TC22, and TC25 (cold/cavity-side tile surface temperatures).

RAH process air flow rates during the April test were controlled at 180, 190, and 200 scfm (5.1, 5.4, and 5.7 m³/min), with 200 scfm (5.7 m³/min) used primarily. Changes in process air flow rates had a definite effect on indicated tile surface temperatures as observed for the January

Figure 3-54. RAH ceramic tile temperatures versus run time for the April test, SFS-RH8-0399.

Figure 3-55. RAH tube surface temperatures versus run time for the April test, SFS-RH8-0399.

Figure 3-56. RAH process air temperatures versus run time for the April test, SFS-RH8-0399.

and February tests. This effect is most evident for process air flow rate changes at Run Hours 80, 95, 109, and 200.

RAH tube surface temperatures ranged from nominally 1390° to 1900°F (755° to 1038°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates had noticeable effects on all tube surface temperatures. Tube surface temperature step changes were most noticeable for surface temperature measurements near the process air exit and on the front side of the tubes. Tube surface temperatures in April were comparable to all previous bituminous coal-fired tests, yet somewhat lower on the high end of the range when compared to the February data.

Process air inlet temperatures ranged from 1145° to 1195°F (619° to 646°C) but was nominally 1160° to 1190°F (644° to 666°C) for most of the coal-fired operational period. Outlet process air temperatures ranged from nominally 1610° to 1710°F (877° to 932°C). The effect of process air flow rate can be seen in the process air outlet temperature data. As process air flow rate decreases, process air exit temperature increases, as expected. These process air flow rate changes are noted at Run Hours 80, 95, 109, and 200.

Heat recovery data from the RAH panel are presented in Figure 3-57 for the April test. At process air flow rates of 180, 190, and 200 scfm (5.1, 5.4, and 5.7 m³/min), the heat recovered from the RAH panel during Kentucky coal firing was 115,385 to 118,750 Btu/hr (121,731 to 125,281 kJ/hr), 115,385 to 119,710 Btu/hr (121,731 to 126,294 kJ/hr), and 120,670 to

Figure 3-57. RAH heat recovery versus run time for the April test, SFS-RH8-0399.

125,000 Btu/hr (127,307 to 131,875 kJ/hr), respectively. The heat recovery ranges are a function of minor adjustments to the coal feed rate and combustion air flow rates. The main burner firing rate was nominally 2.1 to 2.3 MMBtu/hr (2.2 to 2.4×10^6 kJ/hr). Based on the RAH heat-transfer data obtained during the three test periods completed, no conclusion can be drawn concerning the use or nonuse of a coating on the cavity side of the RAH ceramic tiles to improve cavity-side heat transfer.

A comparison of the RAH panel data for the April eastern Kentucky bituminous coal-fired test and the February test firing the same fuel indicates that there was a significant decrease in the heat recovery rate. The decrease appears to be 10% to 15%. During the February test, the heat recovery rate in the RAH panel was 131,730 to 140,385 Btu/hr (138,975 to 148,106 kJ/hr). However, the heat recovery rate observed in April was somewhat higher than the heat recovery rate observed during slagging furnace test periods in 1997 and 1998. EERC personnel believe that the lower heat recovery rate observed in April when compared to February may be the result of the aging of the high-density refractory in the furnace, specifically related to the darkening of the refractory and a potential reduction in its reflectivity.

Figure 3-58 presents heat recovery data for the RAH panel resulting from bituminous coal-fired tests and process air flow rates of 180 and 200 scfm (5.1 and 5.7 m³/min). The data in the figure show that the lowest heat recovery rate was observed in February 1998 (RH3), with the highest heat recovery rate observed in February 1999 (RH7). Because of slight differences in slagging furnace configuration (the presence or absence of the SRAH panel and water-cooled blank door), direct comparisons of RAH heat recovery are only valid for tests completed in the

Figure 3-58. RAH heat recovery for bituminous coal-fired tests completed in 1998 and 1999.

past 6 months (RH6, RH7, RH8, and RH9). Specifically, a comparison of RH7 and RH8 (firing eastern Kentucky coal) shows a decrease in the RAH panel heat recovery rate. These data indicate that the heat recovery rate for the RAH panel is decreasing with each week of operation since the slagging furnace high-density refractory was replaced in late 1998 and the RAH panel was reassembled in January 1999. A comparison between RH6 and RH9 data also support this conclusion. RH9 data are the result of a test completed in May 1999 (SFS-RH9-0499) in support of the Combustion 2000 HiPPS program.

EERC personnel believe that one or two possible factors are causing this change in RAH panel performance relative to heat transfer from the furnace to the radiation cavity. One possibility is a potential change to the RAH ceramic tiles resulting in a decrease in the heat transfer to the radiation cavity. The flame-side surface of the RAH ceramic tiles did darken as a result of slag coating and absorption during the January 1999 test. However, it is not clear what the effect would be on radiant heat absorption or emission, or thermal conductivity. Also, no additional color changes were noted following subsequent test periods. In addition, the changing heat transfer may be related to the tile deterioration with each week of coal-fired furnace operation as a result of slag erosion/corrosion. Erosion/corrosion of the ceramic tiles may be affecting their heat-transfer properties.

Another potential contributing factor to the decreasing heat transfer may be the high-density furnace refractory color change observed with each week of operation. As the high-density refractory has darkened with each week of operation, it is possible that the reflectivity, emissivity, or conductivity of the furnace liner has changed, resulting in a decrease in radiation to the RAH panel. Further testing and data review will be necessary to determine if the observed decrease in RAH panel heat recovery rate continues with each week of testing or if an alternate explanation can be identified.

With completion of the April test, the RAH panel had been exposed to a range of furnace-firing conditions for a total of 1485 hours. Natural gas firing represented 801 hours, and coal/lignite firing represented 684 hours. In addition, the RAH panel was exposed to ten heating and cooling cycles. The RAH ceramic tiles that were installed in January 1999 were exposed to three heating and cooling cycles and 480 hours of slagging furnace operation: 181 hours of natural gas firing (including heatup and cooldown) and 299 hours of coal firing. The longest continuous coal-fired period was 184 hours, completed in April 1999.

3.2 Laboratory- and Bench-Scale Activities

3.2.1 *Dynamic Slag Corrosion Testing*

Modifications were made in the way that the castable refractory blocks are prepared, and four refractory blocks were tested for corrosion resistance in the DSAF during the course of this project. Two modifications were made to the castable blocks to reduce the amount of slag that adheres and flows back under the block where it drips into the furnace rather than out of the exit port. The area directly behind the drip lip was deepened, and a piece of nonwetting platinum foil was attached to the base of the drip lip. A third modification was to deepen the slag well at the

top of the block to allow the slag to pool longer before flowing down the vertical channel. This is especially important later in a test when the exit from the slag pool is corroded, allowing the slag to flow out of the pool too rapidly.

The four refractory blocks tested in the DSAF during this project included three blocks of the experimental Plicast 98 alumina castable prepared and fired to 2958°F (1625°C). Two of them were coated with materials in order to reduce the penetration of slag between the grains. In one case, the slag pool and flow channel were coated with a mixture of colloidal alumina and silica, and for the second block, a suspension of submicron alumina powder was used. The third block was left uncoated as a control. In addition to testing the three castable refractory blocks, a sintered high-alumina material containing 10%–12% chromia, supplied by Kyocera to UTRC, was tested. All of the corrosion tests were performed with Illinois No. 6 slag at 2732°F (1500°C). The airflow rate into the furnace was also reduced from 125 cm³/min (0.004 ft³/min) per entry port to approximately 12.5 cm³/min (0.0004 ft³/min) to reduce the amount of rebound and splash when the unmelted slag particles drop onto the top of the test block.

During the nominally 100-hour tests, slag dripped freely from all of the blocks and did not flow back along their bottoms into the furnace. Surface recession measurements were made on each block after testing. Figure 3-59 is a plot comparing the recession rates with time for the sintered chrome–alumina brick as compared to the fusion-cast Monofrax L and M bricks which were tested previously. Monofrax M is the material used to make the tiles on the front of the LRAH. The plot shows the chrome–alumina refractory had a much lower recession rate than either of the Monofrax materials, although it was found after the tests that there was some variation in slag feed rates during the tests. The feed rate during the chrome–alumina test was

Figure 3-59. Graph of recession with time for the sintered chrome–alumina refractory and the alumina-based fusion-cast Monofrax L and M, tested with Illinois No. 6 slag at 2732°F (1500°C).

approximately 0.09 lb/hr (41 g/hr) per entry port, compared to approximately 0.11 lb/hr (51 g/hr) per entry port when the Monofrax L and M were tested with Illinois No. 6 slag.

Figure 3-60 is a photograph of the chrome–alumina block after 103 hours of slag feed. The photograph shows that the surface of the block has only slightly receded and the discoloration caused by slag penetration into the block, on either side of the vertical channel, is minimal. The erosion of the chrome–alumina block was mainly concentrated at the center, creating a v-shaped channel instead of the usual broad u-shape observed in the Monofrax M block, as shown in Figure 3-61. After 103 hours of slag feed, the chrome-containing block had an average measured recession of 0.09 in. (0.23 cm), which is a rate of 0.0009 in./hr (0.0023 cm/hr). This is a 70% reduction compared with 0.35 in. (0.89 cm) (0.003 in./hr or 0.001 cm/hr) for Monofrax M and a 91% reduction compared to the 0.73 in. (0.29 cm) (0.01 in./hr or 0.004 cm/hr) after 70 hours for Monofrax L. In addition, because of the difference in corrosion channel shapes, the relative volume loss by the chrome–alumina material was much less than the ratios of recession depths would indicate. The much more narrow erosion channel for the chrome–alumina bricks should also substantially reduce the formation of slag flow rivulets that focus the slag corrosion of the Monofrax M panels in the SFS. The recession would most likely have been slightly higher for the chrome–alumina refractory at a slag feed rate of 0.11 lb/hr (51 g/hr), but it is still apparent this refractory holds up very well in the presence of flowing slag.

To address environmental issues related to the disposal of chrome-containing refractories and their spent slag, chemical analysis using TCLP (toxicity characteristic leaching procedure), EPA Test Method 1311, has been completed on a sample of spent slag from the chrome–alumina

Figure 3-60. Photograph of the chrome–alumina block from UTRC after 103 hours of slag feed at 2732°F (1500°C) using Illinois No. 6 slag.

Figure 3-61. Photograph of the Monofrax after 100 hours of slag feed at 2732°F (1500°C) using Illinois No.6 slag.

fusion cast material. The spent slag sample was collected after 9 hours of slag feed. The leachate contained approximately 5 µg of chrome per liter. The measured value is three orders of magnitude below the EPA disposal limit of 5 mg/L and one order of magnitude below the drinking water limit of 50 µg/L. Wavelength-dispersive x-ray fluorescence (WDXRF) analyses were done on two spent slag samples for the chrome–alumina refractory and Plicast 98 materials to determine the amount of chrome removed from the chrome–alumina refractory and to monitor the remaining oxide concentrations. The spent slag samples were collected from the water quench vessel. The first sample was taken after 9 hours of slag feed, and the second was taken at the end of the test, after 103 hours of slag feed. Table 3-10 summarizes the compositions for the slag (Illinois No. 6) and the refractory reactant products as a function of slag flow time.

In general, the numbers stayed fairly constant for both refractory samples. Very little chrome was removed from the chrome–alumina refractory. The greatest changes in oxide concentrations were found in silica and alumina in the slag reactant product for the coated Plicast 98 sample. The silica decreased from 53.8% to 50.6%, and the alumina increased from 19.0% to 21.5% after 103 hours of slag feed. These results are typical, as the recession was also higher for the Plicast 98 material (0.28 in. or 0.71 cm) than the chrome–alumina sample (0.09 in. or 0.23 cm). It was found in previous tests using the Plicast materials, because of their higher porosity than the brick samples, that the silica is lost through penetration into the refractory and the alumina is removed from the refractory material and dissolved into the slag.

Figure 3-62 is a photograph of Plicast 98, an experimental 98% alumina castable developed in cooperation with the Plibrico company, that was prefired to 2957°F (1625°C) and tested at

TABLE 3-10

Illinois No. 6 Slag and Slag Reactant Product Compositions as Determined by WDXRF					
Oxides, wt%	Illinois No. 6 Slag, as-received	9-hour Slag Chrome–Alumina	103-hour Slag Chrome–Alumina	9-hour Slag Coated Plicast	103-hour Slag Coated Plicast 98
SiO ₂	54.4	52.4	52.0	51.6	50.6
Al ₂ O ₃	19.0	19.3	19.3	20.0	21.5
Fe ₂ O ₃	15.6	16.5	16.8	16.5	16.4
TiO ₂	0.7	0.9	0.9	0.9	0.8
P ₂ O ₅	0.0	0.2	0.2	0.2	0.2
CaO	7.1	6.5	6.6	6.5	6.4
MgO	1.3	1.7	1.8	1.8	1.8
Na ₂ O	0.0	0.6	0.6	0.6	0.6
K ₂ O	1.8	1.8	1.8	1.9	1.8
SO ₃	0.0	0.0	0.0	0.0	0.0
Cr	0.0	0.06	0.07	0.02	0.02

Figure 3-62. Photograph of the coated Plicast 98 material that was prefired to 2957°F (1625°C) and tested at 2732°F (1500°C) for 103 hours using Illinois No. 6.

2732°F (1500°C) for 103 hours using Illinois No. 6 slag. This block was coated with a paint consisting of a suspension of silica and alumina particles to help seal pores in the refractory. The corrosion is much more visible, and the discoloration caused by the slag penetration is much more extensive than with the chrome–alumina block or the Monofrax materials. The average recession after 103 hours of slag feed for the coated Plicast 98 sample pre-fired to 2957°F (1625°C) and tested at 2732°F (1500°C) was 0.28 in. (0.71 cm). This is compared to 0.62 in. (1.57 cm) after 54 hours of slag feed for a previously tested uncoated Plicast 98 sample pre-fired and tested at 2732°F (1500°C) shown in Figure 3-63. When comparing Figures 3-62 and 3-63, it is clear that the corrosion/erosion effects are much greater for the uncoated lower pre-fire-temperature block. The vertical channel is much rougher and more eroded than the coated block that was fired to the higher temperature. Overall, the coating and higher pre-firing temperature dropped the corrosion rate by 75%, although as was mentioned with the chrome–alumina block, the feed rate was approximately 0.022 lb/hr (10 g/hr) less for this test. The small reduction in feed rate is not believed to be significant in causing the greatly reduced corrosion rate. It was not clear, however, whether the coating or the higher pre-firing temperature were more responsible for the lower recession rate.

To differentiate between the effects of the coating from those due to the higher pre-fire temperature and to test another coating type, two additional Plicast 98 blocks were prepared, pre-fired to 2957°F (1625°C), and tested at 2732°F (1500°C). One of the blocks was painted with a suspension of alumina particles to seal the pores, and the other was left uncoated as a control to separate the effects of the coating from the higher pre-fire temperature. These two blocks were exposed for 90 hours in the DSAF at 2732°F (1500°C), using Illinois No.6 coal

Figure 3-63. Photograph of uncoated Plicast 98 material that was pre-fired and tested at 2732°F (1500°C) for 54 hours using Illinois No. 6 slag.

slag. The feed rate was approximately 0.11 lb/hr (50 g/hr) per entry port. The block with the painted corrosion-resistant coating had an average measured recession of 0.34 in. (0.86 cm), and the uncoated block had an average measured recession of 0.29 in. (0.74 cm). The slightly higher recession for the block with the paint-on coating shows that this coating was not effective in reducing the corrosion rate with Illinois No. 6 slag, although it may still increase corrosion resistance to more alkaline coal slags. Figure 3-64 is a graph showing the recession depths of the different Plicast 98 blocks. It shows that prefiring to 2910°F (1625°C), rather than 2732°F (1500°C), reduced the corrosion by 70%, and that neither coating increased corrosion resistance to the Illinois No. 6 slag. However, the coatings may be more effective with more basic slags.

3.2.2 *Effect of Additives on Slag Viscosity*

Proper slag flow and slag corrosion are major operational concerns for the HITAF. Since the viscosity for the slag controls its flow characteristics as well as the rate of mass transport of corrodents, it is important to delineate the factors affecting slag viscosity so that accurate predictions of flow and corrosion in different regions of the HITAF can be made. The factors affecting viscosity include slag composition, local atmosphere, and slag temperature. The variable over which the operator has the most control is composition through coal selection or the use of additives. By manipulating the composition of the slag, it may be possible to control slag behavior in ways such as ensuring slag flow through taps or reducing the corrosiveness of the slag by reducing the rate of mass transport of corrodents to the refractory.

Figure 3-64. Plot of recession versus time for Plicast 98 castable material with and without corrosion-resistant coatings.

During this project, changes in viscosity-versus-temperature curves were determined for the Rochelle subbituminous slag for which data have been previously reported and a slag formed in the SFS while CCS lignite was tested in April 1998. The tests were performed under simulated coal combustion conditions as functions of additive composition. These measurements were repeats of others reported in earlier quarterly technical progress reports to show the effects of changes in test procedures on the measured data.

A test matrix was developed to plot the effect of the addition of alumina, calcia, or silica on the viscosity-versus-temperature curves for both slag sources. The test matrix included mix proportions at 10 wt% of each additive. This level of additive should have a minute economic impact on the operation of a HITAF, since a 10 wt% addition on a slag basis is approximately one-fifth of the relative addition on a coal basis as compared to the addition of limestone for capturing sulfur in a pressurized fluidized-bed combustor (PFBC). Also, the additives used in a HITAF melt into the slag and are easily disposed of, even sold as a commercial product, as compared to the highly leachable bed materials produced from a PFBC which are difficult to dispose.

The slags for the viscosity measurements were prepared by first grinding the slag to a -20-mesh (-8.33- μ m) size. A total of 0.22 lb (100 g) of the powdered slag with the appropriate amount of the selected additive oxide was placed in an attrition mill with about 200 mL of isopropanol. The slag slurry was mixed and milled for 1 hour. The slurry was then vacuum-dried and placed in a drying oven at 140°F (60°C) for about 24 hours. The slags were prepared by melting each ash or ash-blend in air in a platinum crucible and then quenching them on a brass plate at room temperature. The slags were crushed, placed in a platinum/rhodium crucible, and reheated to 2732°F (1500°C) to start and the viscosity measured as the temperature was dropped, holding at each temperature until the viscosity stabilized.

Modifications to the viscosity testing procedure were incorporated to better ensure the testing environment was closed to outside contaminants. First, platinum-rhodium crucibles were used instead of alumina which had been used in the past. It was determined earlier that measurable amounts of alumina were dissolving into the slag, which consequently could affect the viscosity measurements. This was considered a potential problem generally while testing slags from lignite and subbituminous coals. The viscometer furnace is a box-type furnace with an alumina tube aligned from the top to the bottom of the furnace. The tube exiting out the bottom of the furnace is sealed with a cap. This is designed to prevent outside gases from entering, as well as minimizing the test gas mixture from seeping out of, the test chamber environment. In addition, an electric steam generator is now being used to regulate the moisture output into the test gas mixture.

Viscosities were measured with a Haake Viscometer® VT550 system which uses a rotating-bob viscometer. The bob, which is made of platinum, is 9 mm in diameter and 20 mm long and has a 45 degree taper at each end. It is submerged into the slag until the slag just covers its top, and then it is rotated at 45.3 rpm. The torque applied to the viscometer is read and converted to an electrical signal that is sent to a computer with a data acquisition program that determines the viscosity of the slag. The viscosity of the slag was measured over the range of 45 to as high as 280 poise unless crystallization was seen to occur along the walls of the alumina container, at

which point the measurement was terminated. In all cases, crystallization occurred before higher-viscosity measurements were possible. Viscosities over 1000 poise are certainly attainable with the VT550 system. The viscometer was calibrated with National Bureau of Standards silicate glass 710a. The accuracy of the viscosity test is approximately 5%. The tests were run in an oxidizing gas environment of 13% CO₂, 4% O₂, 1000 ppm SO₂, and 10% H₂O with a nitrogen balance.

Figure 3-65 shows the viscosity-versus-temperature curves for two repeat measurements of the original Rochelle slag. The figure indicates that the temperature at which the slag has a viscosity of 250 poise, or T_{250} , is approximately 2192°F (1200°C), although this measured temperature can vary up or down by 54°F (30°C) between tests. 250 poise is a benchmark value because at higher viscosities the slag does not flow easily from a combustor. This variability is often seen in more basic slags because they are prone to rapid solidification which is difficult to reproduce. Figure 3-66 shows the viscosity-versus-temperature curves for the original Rochelle slag and the three modified Rochelle slags. The curves indicate that the additions of 10% silica or alumina to the slag have insignificant impacts on the T_{250} , although the alumina addition may increase the propensity for the slag to solidify suddenly upon cooling. The addition of calcia, however, substantially reduces the T_{250} of the slag. This is in contrast to the data measured previously when an alumina crucible was used, which showed that the addition of calcia dropped the T_{250} of the slag only slightly, whereas the addition of alumina and silica greatly increased the T_{250} . The difference in behavior is most likely an indication of the effect of the dissolution of a

Figure 3-65. Viscosity-versus-temperature curves for two repeat measurements of the Rochelle slag.

Figure 3-66. Viscosity-versus-temperature curves for the original and modified Rochelle slags.

small amount of the alumina crucible into the slag in the earlier test, which substantially increased the alumina content of the slag above that attributable to the additive.

Figure 3-67 shows the viscosity-versus-temperature curves for the slag produced in the SFS while the CCS lignite was fired in April of 1998 under separate funding. It indicates that the lignite slag has a T_{250} approximately 270°F (150°C) lower than that of the Rochelle slag. The addition of calcia to the lignite slag appears to slightly reduce the T_{250} , whereas the addition of alumina and silica appears to slightly increase it, although the changes are on the order of the natural variability in the measurement. As was also true for the addition of the alumina to the Rochelle slag, adding alumina to the lignite slag increases its propensity to rapidly solidify near the T_{250} .

3.2.3 Heated-Stage XRD Analysis of Slags

In order to develop a better model of the viscosity-versus-temperature behavior of coal slags, it is necessary to understand the temperature-related crystallization behavior of the slags. To determine the temperature-versus-crystallization behavior of coal slag, a heated-stage x-ray diffraction system is being used. It employs a Philips X'Pert-MPD x-ray diffraction system utilizing a PW3040 console. Attached is a removable Buhler HDK 1.4 high-temperature chamber (heated stage). This system arrangement, called theta-theta, allows the sample to sit still in the heated-stage chamber while the x-ray source and detector rotate about an arc, allowing the sample to be heated to the melting point. The high-temperature chamber consists of a cylindrical,

Figure 3-67. Viscosity-versus-temperature curves for the original and modified CCS lignite slag and modified slags.

double-walled, water-cooled pot made of stainless steel. It is equipped with a beryllium irradiation window and ports for a vacuum/pressure pump and inlet/outlet gases. The sample rests in a depression of a metal strip composed of platinum–rhodium alloy, connected to a power source and controlled by means of a thermocouple physically attached to the sample strip. A computer and software ultimately control the entire diffraction system.

During testing, the sample was heated using a ramp rate of 90°F (50°C) per minute to testing temperatures of 932°, 1832°, 2192°, 2282°, and 2372°F (500°, 1000°, 1200°, 1250°, and 1300°C) and then in increments of 45°F (25°C) to 2912°F (1600°C). Upon cooling, the testing temperatures were in increments of 45°F (25°C) from 2912°F (1600°C) to 2102°F (1150°C), 2012°, 1922°, 1832°, 1472°, and 932°F (1100°, 1050°, 1000°, 800°, 500°C). The system was allowed to equilibrate for 1 minute before scanning. A synthetic combustion gas composed of 14% CO₂, 4% O₂, and 1000 ppm SO₂, with the balance N₂, was introduced into the chamber at a rate of 2 scfh (0.06 m³/hr). Steam was also introduced as a mass fraction of 10% of the gas or 0.2 scfh (0.006 m³/hr).

Under this project, three samples of slags collected from the SFS after the February test of the eastern Kentucky coal were analyzed. X-ray diffraction scans were taken at each temperature interval during heating and also during cooling. The scans were then qualitatively analyzed, noting the presence and/or absence of phases as they related to temperature.

Figures 3-68 and 3-69 show the changes in x-ray diffraction patterns for a sample of slag collected from the slag tap while heating to the melting point, then cooling, respectively. At room temperature, the identified crystalline phases were mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), hercynite (FeAl_2O_4), and hematite (Fe_2O_3). At 1832°F (1000°C), hercynite assimilated into the melt, and a transition phase of plagioclase $[(\text{Ca}, \text{Na})(\text{Al}, \text{Si})_4\text{O}_8]$ was detected, which was not detected above 2462°F (1350°C). Hematite assimilated into the melt at 2642°F (1450°C). By 2822°F (1550°C), the entire sample had melted. When cooling, mullite crystallization could not be detected until 2507°F (1375°C). Hematite crystallization was detected at 2012°F (1100°C), and by 1922°F (1050°C), hercynite could also be detected. Plagioclase did not form during cooling.

Results of analyses of two samples from the slag screen were only slightly different from the slag tap sample. At room temperature, the only detected crystalline phases were mullite and hercynite. Hematite was detected at 1832°F (1000°C) and plagioclase at 2192°F (1200°C). By 2372°F (1300°C), hercynite, hematite, and plagioclase could not be detected. At 2867°F (1575°C), the sample was completely melted. During cooling, mullite crystallization could be detected at 2507°F (1375°C). At 2012°F (1100°C), hercynite was detected, and by 932°F (500°C), hematite could also be detected but did not appear to be present at room temperature. Again, plagioclase did not form during cooling.

Figure 3-68. X-ray diffractograms for the eastern Kentucky slag tap sample measured while heating to the melting point.

Figure 3-69. X-ray diffractograms for the eastern Kentucky slag tap sample measured while cooling from the melting point.

4.0 CONCLUSIONS AND OBSERVATIONS

The objective of the proposed work was to improve the performance of a high-temperature heat exchanger, as well as to develop methods for reducing corrosion of brick and castable refractory in slagging coal-fired combustion systems. Specific technical issues of interest included the effects of coatings on heat transfer in an RAH heat exchanger panel, the general impact of firing a lower-iron bituminous coal on the operation of the RAH panel and SFS, and the development of ways to treat brick and castable refractories to increase their resistance to slag corrosion. Specific conclusions and recommendations concerning fuel characteristics, SFS operation, CAH performance, and RAH panel performance as a result of firing the Illinois No. 6 and eastern Kentucky bituminous coals are discussed here along with those developed based on analytical, laboratory, and bench-scale work to develop methods to prevent excessive corrosion of the heat exchanger components.

4.1 Fuel Characteristics

A comparison of the two bituminous coals fired in the SFS shows that the Illinois No. 6 coal contained twice the moisture (4.4–5.1 wt% versus 2.3–2.5 wt%), four times the sulfur (3.6–3.7 wt% versus 0.8–1.0 wt%), and nearly three times the ash (11.2–11.3 wt% versus

3.9–4.7 wt%). As a result of these fuel characteristics, the heating value of the Kentucky coal was 21%–26% greater than that of the Illinois No. 6 coal, 13,861–14,120 Btu/lb (32,210–32,812 kJ/kg) versus 11,257–11,328 Btu/lb (26,159–26,324 kJ/kg) on an as-fired basis. Therefore, the Kentucky coal was an easier fuel to fire and had fewer operational impacts on the SFS.

Coal ash analyses determined that the Kentucky coal ash contained significantly less silica, more alumina, and somewhat less iron and calcium. These differences in ash composition resulted in ash fusion temperatures that were significantly higher (100° to 200°F, 56° to 111°C) for the Kentucky coal ash. As a result, slag properties caused slag screen plugging which forced an SFS shutdown. Limestone injection was effectively used to mitigate this problem during a subsequent test.

4.2 SFS Performance

When the Illinois No. 6 bituminous coal was fired, the total furnace firing rate (main plus auxiliary burners) ranged from 2.9 to 3.0 MMBtu/hr (3.0 to 3.1×10^6 kJ/hr). The main burner firing rate ranged from 2.1 to 2.25 MMBtu/hr (2.2 to 2.3×10^6 kJ/hr), accounting for 73% to 77% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2775° to 2840°F (1524° to 1560°C).

When the eastern Kentucky bituminous coal was fired, the total furnace firing rate (main plus auxiliary burners) ranged from 2.7 to 2.9 MMBtu/hr (2.8 to 3.0×10^6 kJ/hr). The main burner firing rate ranged from 2.1 to 2.27 MMBtu/hr (2.2 to 2.3×10^6 kJ/hr), accounting for 76% to 82% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2740° to 2830°F (1505° to 1555°C). A lower auxiliary burner firing rate was required to maintain desired slag screen temperatures, possibly the result of the lower moisture content of the eastern Kentucky coal. Operating problems encountered during the February test were related to slag screen plugging and high differential pressure.

The slag tap never plugged, and slag flow through the slag tap was not a problem during either of the three test periods. Reducing the number of tubes in the slag screen and the use of limestone to modify the Kentucky coal slag successfully mitigated the slag screen plugging and differential pressure control problems experienced when we first attempted to fire the eastern Kentucky coal in the SFS.

Inspection of the furnace refractory after the January, February, and April tests indicated that the new high-density refractory was in excellent condition. The only area showing any deterioration was below the RAH panel where slag from the panel was dripping onto the high-density refractory below. The only observed change in the high-density liner as a function of operation is that the color appears to get a little darker with each test, indicating slag penetration into the refractory. This change in appearance may indicate the potential for a failure of the high-density furnace liner if the refractory chemistry is sufficiently modified. Therefore, further work is definitely needed relative to the selection and performance of refractory materials to be used in the commercial HITAF.

The coatings applied to specific areas of the high-density refractory surface to improve its slag corrosion resistance prior to the January test were not evident upon furnace inspection following the test. Apparently the coatings were eroded from or absorbed into the surface of the high-density refractory. The two coatings tested in the slagging furnace were selected based on bench-scale observations. Based on the pilot-scale observations, further bench-scale development work is necessary before additional coating tests occur in the pilot-scale slagging furnace.

In order to modify the slag chemistry and reduce its ash fusion temperature, control slag screen differential pressure, and avoid plugging problems when firing the eastern Kentucky coal, a feed system was set up to add -40-mesh ($-370\text{-}\mu\text{m}$) limestone to the coal at the point it entered the primary air stream. The effectiveness of the limestone addition was evaluated for limestone feed rates ranging from 0.25 to 2 lb/hr (113 to 908 g/hr). Ultimately, slag screen differential pressure was stabilized and effectively controlled at 0.5 in. W.C. (0.9 mmHg) using a limestone feed rate of 0.5 lb/hr (227 g/hr).

Baghouse temperature ranged from 330° to 367°F (166° to 186°C) during the 4 weeks of operation. The 36 bags (total filtration area of 565 ft² [52.5 m²]) used in the baghouse were a 22-oz/yd² (747 g/m²) woven glass with a PTFE membrane. The filter face velocities ranged from 2.4 to 3.0 ft/min (0.74 to 0.91 m/min). Calculated particulate emissions from the pulse-jet baghouse were as low as 0.0014 lb/MMBtu while effectively using on-line cleaning to control differential pressure in the range of <2 to 6 in. W.C. (<3.7 to 11.2 mmHg).

Further work characterizing fly ash generated by the HITAF concept is necessary in order to properly select the type of particulate control technology (electrostatic precipitator, fabric filter, or hybrid system) to be used as well as to prepare detailed system designs and the approach to operation. Based on the SFS pulse-jet baghouse experience to date, there are questions yet to be answered concerning the appropriate filter face velocity, fabric type, and approach to cleaning that will effectively achieve performance objectives relative to particulate emissions and the control of differential pressure for all fuel types.

4.3 CAH Performance

The CAH tube bank was installed and initially evaluated during a shakedown test completed in October 1997. Through April 1999 the CAH tube bank has experienced twelve heatup/cooldown cycles as a result of 1716 hours of coal/lignite (731 hours) and natural gas (985 hours representing SFS heatup/cooldown and refractory curing) firing in the SFS.

Clean tube surface temperatures were nominally 1565°F (852°C), with the surface temperature decreasing to 1340°F (982°C) as ash deposits developed and adjustments were made to the process air flow rate during the tests in January, February, and April 1999.

When coal firing (Illinois No. 6 or eastern Kentucky) began, surface temperatures initially decreased at a rate of nominally 5°F/hr (3°C/hr) for 10 (eastern Kentucky) to 20 hours (Illinois No. 6). After nearly 40 hours of coal firing, there was no further decrease in tube surface temperature for either fuel.

On the basis of CAH data developed during this test series, it appears that the addition of the fins to the air-cooled tubes improved heat recovery during the coal-fired test periods. The fins appear to have reduced the rate of heat-transfer degradation as ash deposits developed and helped to maintain a higher heat-transfer rate once the deposits had formed. However, no improvement in heat recovery was observed during the initial natural gas-fired periods with clean tube surfaces.

The CAH ash deposition rate was a factor of 3 greater when the Illinois No. 6 coal was fired, 0.03 lb/MMBtu ($13.3 \text{ g}/10^6 \text{ kJ}$) versus 0.01 lb/MMBtu ($5.9 \text{ g}/10^6 \text{ kJ}$) when the eastern Kentucky coal was fired. As a result, heat recovery from the CAH tube bank was significantly greater when the eastern Kentucky coal was fired, consistent with the Kentucky coal's lower ash content and higher heating value. However, these data do not address the potential for improved heat recovery for either fuel type as a function of an effective sootblowing system.

CAH tube bank plugging was not a problem when the Illinois No. 6 or eastern Kentucky coal were fired. The deposits that formed were limited to the leading and trailing edges of the tubes. However, when the Illinois No. 6 coal was fired, deposits did bridge the area between the tubes in the direction of the flue gas flow.

In addition to greater mass, deposit strength was greater when the Illinois No. 6 coal was fired. The strength of the Illinois No. 6 deposits was indicated by the fact that the deposits generally remained intact when the CAH tube bank was removed from the duct. Also, the deposits were generally removed intact from the tube surfaces. In contrast, following the eastern Kentucky coal test, the ash deposits from the cooled tubes could not be removed intact from the tube surfaces.

Characterization of the eastern Kentucky ash deposits showed that essentially all of the deposits were composed of complex silicates, except for a thin powder layer adjacent to the tube, which contained approximately 15% sulfate material. The deposits were dominated by larger particles enriched in silica (about 50% silica) and iron and depleted in alumina and calcia. Because all alkali and alkaline earth species were present in very low concentrations, limited deposit sintering at the temperatures of the CAH was observed.

4.4 RAH Performance

Initial shakedown and testing of the RAH panel took place in December 1997. Through April 1999, the RAH panel has experienced ten heatup/cooldown cycles as a result of 1485 hours of coal/lignite (684 hours) and natural gas (801 hours representing SFS heatup/cooldown and refractory curing) firing in the SFS. The new ceramic tiles that were installed in January 1999 were exposed to three heating and cooling cycles and 480 hours of slagging furnace operation: 181 hours of natural gas firing (including heatup and cooldown) and 299 hours of coal firing.

The hairline cracks found in new RAH ceramic tiles are believed to result from stresses encountered during tile fabrication, the actual casting/cooling process, and the machining of the tiles. These stresses and the resulting cracks could be reduced if the tiles could be formed in near net shapes, eliminating the need for machining.

Exposure of the RAH ceramic tiles to slag during coal firing in January darkened the tiles as a result of the residual slag layer on the surface. No additional tile color change was evident following the February and April tests.

Following the April test, cracks were evident in four of the five tiles. In general, none of the cracks indicated the potential for a near-term tile failure. However, the combination of cracks in the small and larger upper tiles could be problematic with further heating and cooling cycles. Heatup/cooldown cycles are believed to contribute significantly to the RAH panel ceramic tile/brick cracking and the propagation of cracks formed during tile fabrication.

Overall, the condition of the ceramic tiles deteriorated somewhat with each test, with the small lower tile showing the greatest degree of erosion/corrosion. This is believed to result from the combination of its higher surface temperature and the greater quantity of slag flowing over its surface relative to the other tiles.

The highest RAH heat recovery rate was observed in February 1999 (eastern Kentucky coal), with fuel quality believed to be the reason for the lower heat recovery rate in January (Illinois No. 6 coal). Overall, the data indicate that the heat recovery rate for the RAH panel is decreasing with each week of operation since the slagging furnace high-density refractory was replaced in late 1998 and the RAH panel was reassembled in January 1999.

Possible contributing factors to the degradation of RAH panel performance relative to heat transfer from the furnace to the RAH tubes include 1) changes to the ceramic tiles on the flame-side surface as a result of slag coating and/or erosion/corrosion of the ceramic tile surfaces and 2) changes in the reflectivity or emissivity characteristics of the high-density furnace refractory as a result of slag adsorption/absorption and the darkening of the furnace liner.

Based on the RAH heat-transfer data obtained during the three test periods completed, no conclusion can be drawn concerning the use or nonuse of a coating on the cavity side of the RAH ceramic tiles to improve cavity-side heat transfer.

Increasing heat exchanger efficiencies and material lifetimes demonstrates to coal-burning utilities that coal-fired options exist and it may not be necessary to switch to natural gas firing or purchase CO₂ credits if CO₂ emission restrictions are legislated. Instead, existing coal-burning boilers can be repowered with an indirectly fired turbine combined cycle to increase efficiency by up to 50% and reduce CO₂ emissions by as much as 40%.

4.5 Bench and Laboratory Corrosion Testing

Bench-scale testing with the DSAF showed that a new sintered chrome–alumina refractory brick material prepared by Kyocera is at least 70% more resistant to flowing slag corrosion than the fusion cast alumina material currently in use in the RAH. In addition, the corrosion channel was much narrower than for the fusion cast material, so actual service lifetime may be substantially better than indicated by the 70% reduction figure. Also, TCLP tests showed that the slag flowing over the Kyocera material does not absorb enough chromia to become a disposal

problem. Other DSAF tests show that prefiring an experimental 98% alumina castable refractory to 2957°F (1625°C) reduces the corrosion rates by 75% as compared to material prefired to only 2732°F (1500°C). Coatings used to seal the pores of the refractory were ineffective at reducing corrosion rates by Illinois No. 6 slag, but may be effective for more basic slags.

Slag viscosity testing showed that there can be considerable variation in the temperature below which the slag does not flow well for basic slags which tend to freeze rapidly. However, adding 10% calcia to a high-calcium Rochelle slag substantially reduced the freezing temperature of the slag. Alumina and silica additions had little effect. Additions of calcia, alumina, or silica to a lignite slag had little effect on the flow properties of a lignite slag, although the alumina addition may increase its propensity to freeze quickly upon cooling. However, the freezing temperature is still too low to make a 10% addition effective in causing the slag to freeze on the refractory in a combustor system, which would decrease the corrosion rate of the refractory.

5.0 RECOMMENDATIONS FOR FUTURE WORK

Based on the data developed during the Combustion 2000 Project, we conclude that the HITAF concept offers a higher-efficiency technology option for coal-fired power generation systems than conventional pc firing. Higher-efficiency technology options are important to the power generation industry in order to conserve valuable fossil fuel resources, reduce the quantity of pollutants (air and water) and solid wastes generated per MW, and reduce the cost of power production in a deregulated industry.

A number of accomplishments have been achieved as a result of the bench- and pilot-scale work summarized in this report, as well as the work completed to date in support of the Combustion 2000 Program. On the basis of results and observations from both activities, the EERC believes that further development and evaluation of the high-temperature heat exchangers and materials related to their successful use are warranted. Specific activities to be considered are summarized in the following paragraphs.

New high-density castable refractory and castable ceramic formulations were developed in cooperation with commercial vendors. These new materials are more resistant to the erosive/corrosive properties of slag than those initially evaluated. In addition, higher curing temperatures were successfully applied to high-density castable refractories, resulting in improved resistance to slag erosion/corrosion. However, further development of these materials for use in high-temperature furnace applications with emphasis on their resistance to slag erosion/corrosion is necessary before commercial application will be possible.

Partial success was achieved with respect to casting ceramic tiles in near net shapes, limiting the need for machining and thus reducing stress cracking. However, further development of ceramic component fabrication methodology with an emphasis on casting near net shapes to eliminate machining requirements is necessary to eliminate RAH tile stress cracking and reduce the cost of RAH ceramic tiles.

Bench-scale tests successfully demonstrated the use of additives to modify slag properties. Specifically, additives were successfully used to increase and decrease slag viscosity for acidic and basic slags. Bench-scale tests with an alumina additive were successful in reducing refractory corrosion. During pilot-scale tests, limestone added to the pulverized fuel was successfully used to prevent slag screen plugging and control differential pressure. On the basis of these observations, further development of coatings that can be applied to refractory or ceramic surfaces to effect the desired changes in heat transfer or improve the resistance of these materials to slag erosion/corrosion is warranted.

Bench-scale tests have been used to identify a high-temperature window in which the products of coal combustion are much less corrosive toward the alloy MA-754 used to fabricate tubes for the RAH panel. This information indicates it would be appropriate to determine the potential to operate the RAH panel without fireside ceramic tile protection at furnace exit temperatures comparable to those found in conventional pc-fired boilers. This information would be very valuable in determining the potential application of the MA-754 alloy to repowering projects.

The pilot-scale SFS has been successfully operated in support of the high-temperature heat exchanger development effort firing lignite, subbituminous coal, or bituminous coal. CAH tube bank performance has been problem free when these fuel types are fired, resulting in process air temperatures of nominally 1300°F (705°C). Successful operation of the RAH panel when the same fuels are fired has also been demonstrated, resulting in process air temperatures of 1700° to 2000°F (927° to 1094°C). Therefore, further development and testing of the high-temperature heat exchanger are warranted. Specific activities should address 1) investigation of alternative alloy and ceramic materials that will permit operation of the RAH panel at temperatures higher than these observed to date for process air temperatures of >2000°F (>1094°C), 2) corrosion testing of alloy materials for fireside applications, 3) integrated operation of the CAH tube bank and RAH panel with a turbine, 4) integrated operation of the CAH tube bank and RAH panel with a fuel cell, and 5) cofiring biomass in the high-temperature SFS and documenting overall system performance as well as specific efficiency losses that may occur relative to the performance of the CAH tube bank and the RAH panel.

On the basis of work completed to date, the HITAF concept appears to offer a higher-efficiency technology option for coal-fired power generation systems than conventional pc firing. Concept analyses have demonstrated the ability to achieve program objectives for emissions (10% of New Source Performance Standards, i.e., 0.003 lb/MMBtu of particulate), efficiency (47%–55%), and cost of electricity (10%–25% below today's cost). Higher-efficiency technology options for new plants as well as repowering are important to the power generation industry in order to conserve valuable fossil fuel resources, reduce the quantity of pollutants (air and water) and solid wastes generated per MW, and reduce the cost of power production in a deregulated industry.

Possibly more important than their potential application in a new high-temperature power system, the RAH panel and CAH tube bank are potential retrofit technology options for existing coal-fired boilers to improve plant efficiencies. Therefore, further development of these process

air-based high-temperature heat exchangers and their potential for commercial application is directly applicable to the development of enabling technologies in support of the Vision 21 program objectives.