

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

Dr. Arun Bose
Contracting Officer's Technical Representative

Prepared by:

Michael E. Collings
Bruce A. Dockter
Douglas R. Hajicek
Ann K. Henderson
John P. Hurley
Patty L. Kleven
Greg F. Weber

Energy & Environmental Research Center
University of North Dakota
PO Box 9018
Grand Forks, ND 58202-9018

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report is available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

EERC DISCLAIMER

LEGAL NOTICE This research report was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by the U.S. Department of Energy National Energy Technology Laboratory. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

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.

TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	x
GLOSSARY OF TERMS AND DEFINITIONS	xi
EXECUTIVE SUMMARY	xiv
1.0 INTRODUCTION	1
2.0 EXPERIMENTAL APPROACH	2
2.1 Scope of Work	2
2.1.1 Task 1 – Evaluation of Heat Exchanger Performance in the SFS	2
2.1.2 Task 2 – Bench-Scale Testing of Methods to Reduce Slag Corrosion ..	4
2.2 Description of Pilot-Scale SFS	5
2.2.1 Fuel Feed System	8
2.2.2 Slagging Furnace	10
2.2.3 Radiant Air Heater Panels	14
2.2.4 Slag Screen	15
2.2.5 Dilution/Quench Zone	17
2.2.6 Convective Air Heater	17
2.2.7 Process Air Preheaters	18
2.2.8 Slagging Furnace System Heat Exchangers	19
2.2.9 System Fans	20
2.2.10 Emission Control	20
2.2.11 Instrumentation and Data Acquisition	22
2.3 Dynamic Slag Application Furnace	22
3.0 RESULTS AND DISCUSSION	23
3.1 Pilot-Scale Testing	23
3.1.1 Pilot-Scale SFS Performance	23
3.1.2 CAH Tube Bank Performance	57
3.1.3 RAH Panel Performance	71
3.2 Laboratory- and Bench-Scale Activities	89
3.2.1 Dynamic Slag Corrosion Testing	89
3.2.2 Effect of Additives on Slag Viscosity	95
3.2.3 Heated-Stage XRD Analysis of Slags	98
4.0 CONCLUSIONS AND OBSERVATIONS	101
4.1 Fuel Characteristics	101
4.2 SFS Performance	102

TABLE OF CONTENTS (continued)

4.3	CAH Performance	103
4.4	RAH Performance	104
4.5	Bench and Laboratory Corrosion Testing	105
5.0	RECOMMENDATIONS FOR FUTURE WORK	106

LIST OF FIGURES

2-1	Photograph of the pilot-scale slagging furnace system	6
2-2	Combustion 2000 slagging furnace and support systems	7
2-3	Illustration of the uncooled tubes in the CAH tube bank	18
2-4	Schematic of the DSAF	22
3-1	Coal feed rate versus run time for the January 1999 test, SFS-RH6-0199	24
3-2	Coal feed rate versus run time for the February 1999 test, SFS-RH7-0299	25
3-3	Coal feed rate versus run time for the April 1999 test, SFS-RH8-0399	25
3-4	Furnace and slag screen temperatures versus run time for the January 1999 test, SFS-RH6-0199	30
3-5	Slagging furnace firing rate versus run time for the January 1999 test, SFS-RH6-0199	31
3-6	Furnace and slag screen temperatures versus run time for the February 1999 test, SFS-RH7-0299	33
3-7	Slagging furnace firing rate versus run time for the February 1999 test, SFS-RH7-0299	34
3-8	Furnace and slag screen temperatures versus run time for the April 1999 test, SFS-RH8-0399	35
3-9	Slagging furnace firing rate versus run time for the April 1999 test, SFS-RH8-0399	36
3-10	Photograph of slag screen tubes following the January test	38
3-11	Photograph of slag screen tubes following the February test	39
3-12	Slag screen differential pressure versus run time for the April 1999 test, SFS-RH8-0399	43
3-13	Photograph of slag screen tubes following the April test	45

LIST OF FIGURES (continued)

3-14	Process air preheater temperatures versus run time for the January test, SFS-RH6-0199	46
3-15	Process air preheater temperatures versus run time for the February test, SFS-RH7-0299	47
3-16	Process air preheater temperatures versus run time for the April test, SFS-RH8-0399	47
3-17	Respirable mass emission data for the January (top) and February (bottom) tests	52
3-18	Respirable mass emission data for the April test	53
3-19	Baghouse hopper ash particle-size data	53
3-20	Multicyclone data resulting from baghouse inlet sampling	54
3-21	Baghouse differential pressure versus run time for the April test	55
3-22	CAH tube surface and flue gas temperatures versus run time for the January test, SFS-RH6-0199	57
3-23	CAH process air temperatures versus run time for the January test, SFS-RH6-0199	58
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	58
3-25	Thermocouple locations in the CAH tube bank	59
3-26	CAH heat recovery versus run time for the January test, SFS-RH6-0199	61
3-27	Photograph of ash deposits on the CAH tubes following the January test firing Illinois No. 6 bituminous coal	62
3-28	CAH tube surface and flue gas temperatures versus run time for the February test, SFS-RH7-0299	63
3-29	CAH process air temperatures versus run time for the February test, SFS-RH7-0299	63
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	64

LIST OF FIGURES (continued)

3-31 CAH heat recovery versus run time for the February test, SFS-RH7-0299 64

3-32 Photograph of ash deposits on the CAH tubes following the February test firing eastern Kentucky bituminous coal 66

3-33 CAH tube surface and flue gas temperatures versus run time for the April test, SFS-RH8-0399 67

3-34 CAH process air temperatures versus run time for the April test, SFS-RH8-0399 68

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 68

3-36 CAH heat recovery versus run time for the April test, SFS-RH8-0399 69

3-37 Photograph of ash deposits on the CAH tubes following the April test firing eastern Kentucky and Illinois No. 6 bituminous coal 70

3-38 Photograph of new ceramic tiles installed on the RAH panel inside of the slagging furnace in January 1999 72

3-39 Photographs of the RAH panel inside of the slagging furnace following the January (top) and February (bottom) tests 73

3-40 Photograph of the RAH panel inside of the slagging furnace following the April test . . . 74

3-41 Illustrations of cracks found in the ceramic tiles/bricks of the RAH panel after testing in January (left) and February (right) 1999 74

3-42 Illustration of cracks found in the ceramic tiles/bricks of the RAH panel after testing in April 1999 75

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 76

3-44 Photograph of the RAH panel from inside of the furnace following the April test 77

3-45 RAH ceramic tile temperatures versus run time for the January test, SFS-RH6-0199 . . 77

3-46 RAH tube surface temperatures versus run time for the January test, SFS-RH6-0199 . . 78

3-47 RAH process air temperatures versus run time for the January test, SFS-RH6-0199 . . . 78

LIST OF FIGURES (continued)

3-48 Thermocouple locations in the RAH panel 79

3-49 RAH heat recovery versus run time for the January test, SFS-RH6-0199 81

3-50 RAH ceramic tile temperatures versus run time for the February test, SFS-RH7-0299 . 82

3-51 RAH tube surface temperatures versus run time for the February test, SFS-RH7-0299 . 82

3-52 RAH process air temperatures versus run time for the February test, SFS-RH7-0299 . . 83

3-53 RAH heat recovery versus run time for the February test, SFS-RH7-0299 84

3-54 RAH ceramic tile temperatures versus run time for the April test, SFS-RH8-0399 85

3-55 RAH tube surface temperatures versus run time for the April test, SFS-RH8-0399 86

3-56 RAH process air temperatures versus run time for the April test, SFS-RH8-0399 86

3-57 RAH heat recovery versus run time for the April test, SFS-RH8-0399 87

3-58 RAH heat recovery for bituminous coal-fired tests completed in 1998 and 1999 88

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) 90

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 91

3-61 Photograph of the Monofrax after 100 hours of slag feed at 2732°F (1500°C) using Illinois No. 6 slag 92

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 93

3-63 Photograph of uncoated Plicast 98 material that was prefired and tested at 2732°F (1500°C) for 54 hours using Illinois No. 6 slag 94

3-64 Plot of recession versus time for Plicast 98 castable material with and without corrosion-resistant coatings 95

LIST OF FIGURES (continued)

3-65 Viscosity-versus-temperature curves for two repeat measurements
of the Rochelle slag 97

3-66 Viscosity-versus-temperature curves for the original and modified Rochelle slags 98

3-67 Viscosity-versus-temperature curves for the original and modified CCS lignite slag and
modified slags 99

3-68 X-ray diffractograms for the eastern Kentucky slag tap sample measured while heating
to the melting point 100

3-69 X-ray diffractograms for the eastern Kentucky slag tap sample measured while cooling
from the melting point 101

LIST OF TABLES

2-1	Theoretical Flow and Heat-Transfer Data for the Slagging Furnace System	11
2-2	Refractory Properties	13
2-3	Pressure, Temperature, and Flow Specifications for the SFS Fans	20
3-1	Results of Coal and Coal Ash Analysis for Coal-Fired Slagging Furnace Tests	26
3-2	Results of Lignite and Lignite Ash Analysis for Lignite-Fired Slagging Furnace Tests . .	27
3-3	February Kentucky Coal Ash, Slag Pot, and Slag Tap Samples	40
3-4	February Kentucky Coal Ash and Slag Screen Samples	40
3-5	April Kentucky Coal Ash and Slag Tap Samples	44
3-6	Flue Gas Emissions for Illinois No. 6 and Kentucky Coal-Fired Slagging Furnace Tests	56
3-7	Description of CAH Thermocouple Locations	60
3-8	CAH Deposit Samples from the February Test	66
3-9	Description of RAH Panel Thermocouple Locations	80
3-10	Illinois No. 6 Slag and Slag Reactant Product Compositions as Determined by WDXRF	93

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/cool-down cycles as a result of 1485 hours of coal/lignite (684 hours) and natural gas (801 hours representing SFS heatup/cool-down 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 cool-down) 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 cool-down 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 cool-down 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 pre-firing an experimental 98% alumina castable refractory to 2957°F (1625°C) reduces the corrosion rates by 75% as compared to material pre-fired 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.