FINAL

***Engineering Development of Coal-Fired High
Performance Power Systems
Phase II and III***

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Quarterly Progress Report

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Abstract

This report presents work carried out under contract DE-AC22-95PC95144 "Engineering Development of Coal-Fired High Performance Systems Phase II and III." The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) that is capable of:

- ◇ thermal efficiency (HHV) $\geq 47\%$
- ◇ NO_x, SO_x, and particulates $\leq 10\%$ NSPS
(New Source Performance Standard)
- ◇ coal providing $\geq 65\%$ of heat input
- ◇ all solid wastes benign
- ◇ cost of electricity $\leq 90\%$ of present plants

Phase I, which began in 1992, focused on the analysis of various configurations of indirectly fired cycles and on technical assessments of alternative plant subsystems and components, including performance requirements, developmental status, design options, complexity and reliability, and capital and operating costs. Phase I also included preliminary R&D and the preparation of designs for HIPPS commercial plants approximately 300 MWe in size. This phase, Phase II, involves the development and testing of plant subsystems, refinement and updating of the HIPPS commercial plant design, and the site selection and engineering design of a HIPPS prototype plant.

Work reported herein is from:

- ◇ Task 2.2 HITAF Air Heaters;
- ◇ Task 6 HIPPS Commercial Plant Design Update

Table of Contents

Abstract	i
Table of Contents	iii
List of Exhibits	v
Executive Summary	ix
Task 2.2 HITAF Air Heaters	ix
Task 6 HIPPS Commercial Plant Design Update.....	xii
Introduction	xiii
Task 2.2 HITAF Air Heaters	2.2-1
Pilot-Scale Testing	2.2-1
Pilot-Scale SFS.....	2.2-1
Pilot-Scale SFS Operation	2.2-13
Testing of the CAH Tube Bank.....	2.2-25
Testing of the LRAH Panel	2.2-31
Testing of the SRAH Panel	2.2-42
Materials	2.2-49
Refractory Materials for the Radiant Air Heaters.....	2.2-49
Laboratory- and Bench-Scale Activities	2.2-77
Task 6 HIPPS Commercial Plant Design Update	6-1
HIPPS Repowering.....	6-1
Site Selection.....	6-1
Cycle Analysis	6-1

List of Exhibits

Exhibit 2.2-1	Combustion 2000 Slagging Furnace and Support Systems	2.2-2
Exhibit 2.2-2	Theoretical Flow and Heat-Transfer Data for Combustion 2000 Slagging Furnace and Refractory Ducts – Illinois No. 6 Bituminous	2.2-5
Exhibit 2.2-3	Refractory Properties	2.2-7
Exhibit 2.2-4	Illustration of the New Uncooled Tubes installed in the CAH Tube Bank	2.2-11
Exhibit 2.2-5	Photograph of the New Uncooled Tubes Installed in the CAH Tube Bank	2.2-11
Exhibit 2.2-6	Pressure, Temperature, and Flow Specifications for SFS Fans	2.2-12
Exhibit 2.2-7	Coal Feed Rate Versus Run Time for the August 1998 Test Period	2.2-14
Exhibit 2.2-8	Results of Coal and Coal Ash Analysis for Coal-Fired Slagging Furnace Tests ¹	2.2-15
Exhibit 2.2-9	Results of Lignite and Lignite Ash Analysis for Lignite-Fired Slagging Furnace Tests ¹	2.2-16
Exhibit 2.2-10	Furnace and Slag Screen Temperatures Versus Run Time for the August 1998	2.2-17
Exhibit 2.2-11	Slagging Furnace Firing Rate Versus Run Time for the August 1998 Test Period	2.2-18
Exhibit 2.2-12	Photograph of Slag Screen Tubes Following the August 1998 Test Period	2.2-21
Exhibit 2.2-13	Cooling Air Preheater Temperatures Versus Run Time for the August Test Period	2.2-23
Exhibit 2.2-14	Flue Gas Emissions for Illinois No. 6 Coal-Fired Slagging Furnace Tests	2.2-25
Exhibit 2.2-15	CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the August Test Period	2.2-26
Exhibit 2.2-16	CAH Cooling Air, LRAH Cooling Air, Quench Gas, and Flue Gas Flow Rates Versus Run Time for the August Test Period	2.2-26
Exhibit 2.2-17	CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the August Test Period	2.2-27
Exhibit 2.2-18	Thermocouple Locations in the CAH Tube Bank	2.2-27
Exhibit 2.2-19	Description of CAH Thermocouple Locations ¹	2.2-28
Exhibit 2.2-20	CAH Heat Recovery Versus Run Time for the August Test Period	2.2-29
Exhibit 2.2-21	Photographs of Ash Deposits on the CAH Tubes Following the August Test Period Firing Illinois No. 6 Bituminous Coal	2.2-30
Exhibit 2.2-22	Photograph of LRAH and SRAH Panels Inside of the Slagging Furnace Following the August Test Period	2.2-32
Exhibit 2.2-23	Illustration of Cracks Found in the Ceramic Tiles/Bricks of the LRAH Panel after Testing in August 1998	2.2-33
Exhibit 2.2-24	Photographs of the LRAH Tubes from Inside the Furnace	2.2-35

Exhibit 2.2-25	LRAH Ceramic Tile Temperatures Versus Run Time	2.2-36
Exhibit 2.2-26	LRAH Tube Surface Temperatures Versus Run Time for the August Test Period	2.2-37
Exhibit 2.2-27	LRAH Cooling Air Temperatures Versus Run Time for the August Test Period	2.2-37
Exhibit 2.2-28	Thermocouple Locations in the LRAH Panel	2.2-38
Exhibit 2.2-29	Description of LRAH Panel Thermocouple Locations ¹	2.2-39
Exhibit 2.2-30	LRAH Heat Recovery Versus Run Time for the August Test Period	2.2-41
Exhibit 2.2-31	Illustration of Cracks Found in the Ceramic Tiles/Bricks of the SRAH Panel after Testing in August 1998	2.2-43
Exhibit 2.2-32	Photographs of the SRAH Ceramic Tiles after the August Test Period	2.2-44
Exhibit 2.2-33	SRAH Ceramic Tile Temperatures Versus Run Time for the August Test Period	2.2-46
Exhibit 2.2-34	Thermocouple Locations in the SRAH Panel	2.2-47
Exhibit 2.2-35	Description of SRAH Panel Thermocouple Locations ¹	2.2-48
Exhibit 2.2-36	SRAH Heat Recovery Versus Run Time for the August Test Period	2.2-49
Exhibit 2.2-37	Furnace Run Summary – Furnace Test Facility at UNDEERC	2.2-51
Exhibit 2.2-38	Location of Large and Small RAH Refractory Tiles	2.2-52
Exhibit 2.2-39	Dimensions of the Center Radiation Tile (LRAH)	2.2-53
Exhibit 2.2-40	Location of Thermocouples on Back (Cool) Face of Radiant Heat Tiles (Labeled B in Exhibit 2.2-38) in the LRAH	2.2-54
Exhibit 2.2-41	Back Face LRAH Ceramic Tile Temperatures vs. Run Time for the First Furnace Run Fired with Natural Gas at 75% Load (LRAH Run No. 1)	2.2-55
Exhibit 2.2-42	Back Face LRAH Ceramic Tile Temperatures vs. Run Time for Natural Gas- and Coal-Fired Tests at 100% Load (LRAH Run No. 2)	2.2-56
Exhibit 2.2-43.	Location of Cracks in the Monofrax M Tiles of the LRAH Panel after the First Furnace Run with Natural Gas at 75%, and Later at 100% Load	2.2-57
Exhibit 2.2-44	LRAH Top Ceramic Block and Tile (A), and Large Middle Tiles (B) after the Coal-Fired Test at 100% Load (Run No. 2)	2.2-58
Exhibit 2.2-45	Location of Cracks in LRAH Tiles after LRAH Runs No. 4, No. 6, and No. 7 in the UNDEERC Pilot Test Facility	2.2-59
Exhibit 2.2-46	Replacement of Top Cross Panel and Radiation Panel in LRAH on Left Side, and Installation of SRAH Panels on Right Side after LRAH Run No. 4. The Dark Top Vertical left Panel in the SRAH has been Coated with Cr-Oxide. (B) Shows the Slag Coated RAH Panels after LRAH Run No. 5 using Natural Gas and Falkirk Lignite.	2.2-61
Exhibit 2.2-47	Typical Composition of Major Constituents in Coal Slags	2.2-62
Exhibit 2.2-48	Back Face LRAH Ceramic Tile Temperatures versus Run Time for the June Test Period (LRAH Run No. 6)	2.2-63

Exhibit 2.2-49	Back Face LRAH Ceramic Tile Temperature vs. Furnace Run Time in August (LRAH Run No. 7)	2.2-64
Exhibit 2.2-50	Top Monofrax L Tile from SRAH after First Falkirk Lignite Firing (SRAH Run No. 1).	2.2-65
Exhibit 2.2-51	Cross-Section of Sample from Top Monofrax L Tile in Contact with Slag after First Falkirk Lignite Firing (SRAH Run No. 1)	2.2-66
Exhibit 2.2-52	Electron Microprobe Maps of Region Adjacent to Slag Contact Surface of Monofrax L Sample Shown in Exhibit 2.2-51	2.2-67
Exhibit 2.2-53	Electron Microprobe Maps of Region Near Slag Surface of Monofrax L Sample Shown in Exhibit 2.2-51	2.2-69
Exhibit 2.2-54	Location of Cracks in SRAH Tiles after SRAH Furnace Runs No. 2 and No. 3 in the UNDEERC Test Facility	2.2-71
Exhibit 2.2-55	Sections cut through Monofrax L crucible (A) and Monofrax M crucible (B) after reactions with contained Illinois No. 6 slag for 100 hours at 2640°F (1450°C) in air	2.2-73
Exhibit 2.2-56A	Electron Probe Element Maps of Sections Through Monofrax L Crucible Shown in Exhibit 2.2-55, Containing Illinois No. 6 Slag at 2640°F (1450°C) for 100 hours in Air	2.2-74
Exhibit 2.2-56B	Electron Probe Element Maps of Sections Through Monofrax M Crucible Shown in Exhibit 2.2-55, Containing Illinois No. 6 Slag at 2640°F (1450°C) for 100 hours in Air	2.2-75
Exhibit 2.2-57	Front View of Monofrax L and M Test Specimens Exposed to Flowing Illinois No. 6 Slag at 2732°F (1500°C) for 70 Hours	2.2-76
Exhibit 2.2-58	Eroded (Shaded) Portion of Monofrax L (A) and Monofrax M (B) Test Specimens Shown in Exhibit 2.2-57	2.2-77
Exhibit 2.2-59	Photograph Showing a Cross Section of the Plicast 99 Block that was Fired to 2910°F (1600°C) and became Saturated with Coal Creek Slag	2.2-78
Exhibit 2.2-60	Photograph Showing Large Expansion Crack that Formed on the Back of the Plicast 99 Block that was Fired to 2910°F (1600°C) and became Saturated with Coal Creek Slag	2.2-79
Exhibit 2.2-61	Photograph Showing Plicast 99 Block that was Fired to 2732°F (1500°C) Deformed Plastically when it became Saturated with Coal Creek Slag	2.2-81
Exhibit 2.2-62	Graph Comparing Surface Recession with Time for Monofrax L using Illinois No. 6 Slag and Coal Creek Slag	2.2-82
Exhibit 2.2-63	Graph Comparing Average Surface Recession with Time for Monofrax M using Illinois No. 6 Slag and Coal Creek Slag	2.2-83
Exhibit 2.2-64	Graph Comparing Average Slag Penetration for each Level of the SFS Combustor	2.2-84
Exhibit 6-1	Comparison of HAT Cycles	6-2
Exhibit 6-2	Simplified HIPPS/HAT	6-3

Executive Summary

This report represents work carried out under contract DE-AC22-95PC95144 “Engineering Development of Coal-Fired High Performance Systems Phase II and III.” The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) that is capable of:

- ◇ $\geq 47\%$ thermal efficiency (HHV)
- ◇ NO_x , SO_x , and particulates $\leq 10\%$ NSPS
- ◇ coal providing $\geq 65\%$ of heat input
- ◇ all solid wastes benign
- ◇ cost of electricity $\leq 90\%$ of present plant

Work reported in this report is from Task 2.2 HITAF Air Heaters and Task 6 HIPPS Commercial Plant Design Update.

Task 2.2 HITAF Air Heaters

The pilot-scale SFS was operated once in support of coal-fired LRAH and SRAH panel tests

Dates	Coal Type	Purpose
August 7-19	Illinois No. 6 coal	Very high temp. test

The following comments summarize the performance of each of the components and/or subsystems during the EERC test conducted during the quarter.

- The fuel feed system was operated in August for 116 hr with Illinois No. 6 coal at nominal feed rates of 190 to 200 lb/hr (86 to 91 kg/hr) in an attempt to maintain a flue gas temperature near the RAH tile surfaces of 2800°F (1538°C). Specific tests were also completed at coal feed rates of 180 and 210 lb/hr (82 and 95 kg/hr). During the test, the coal feed rate was quite stable except for a few spikes (high and low) associated with coal hopper refill cycles. Once furnace refractory curing was completed, the total furnace-firing rate (main plus auxiliary burners) ranged from 2.8 to 3.2 MMBtu/hr (2.9 to 3.3 x 10⁶ kJ/hr). The main burner accounted for 75% of the total energy input.
- Over the course of 116 hr of coal firing during the August test period, the slag tap never plugged and slag flow was not a problem.
- The main and auxiliary burners performed well during the August test. Main burner swirl adjustment was more than adequate to establish a stable flame when the Illinois No. 6 coal was fired. At this time, the EERC plans to operate the slagging furnace using minimum-to-moderate primary 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.

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- Inspection of the slag screen and high density refractory following the August test period indicated that the additional cooling significantly reduced slag penetration and erosion/corrosion of the high-density refractory. However, the first two rows of tubes had been lost to a combination of inadequate water flow rate and a water leak. Inspection of the first two rows of slag screen tubes visible from the inlet side show signs of erosion/corrosion, while the tubes visible from the outlet side appear to have a uniform layer of slag on the surface.
 - Collected material indicates that over 75% of the coal ash were captured in the system as slag.
 - During the August 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-line
 - Although the cooling air preheater heat-transfer rate degraded with time as ash deposits developed on the tube surfaces, cooling air temperature and flow rate control were adequate to support operation of the CAH tube bank and the LRAH panel.
 - Particulate collection efficiency was roughly 99.1% when the Illinois No. 6 bituminous coal was fired in August.
 - While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 40,000 to 45,000 Btu/hr (42,200 to 47,475 kJ/hr). The cooling air flow rate was 120 to 135 scfm (3.4 to 3.8 m³/min). The inlet cooling air was 1110° to 1200°F (599° to 649°C), outlet cooling air was 1360° to 1390°F (738° to 755°C), . As ash deposits developed on the tube surfaces, heat recovery from the CAH tube bank decreased from roughly 40,000 Btu/hr (42,200 kJ/hr) to 26,800 Btu/hr (28,274 kJ/hr). Heat recovery from the CAH tube bank remained at this level for nearly 30 hr of coal firing before further degradation was observed. Over the last 37 hr of coal firing, heat recovery degraded from 26,800 to 16,700 Btu/hr (28,274 to 17,618 kJ/hr).
 - On the basis of these CAH 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.
 - One of the objectives of the August test was to produce 2000°F (1094°C) air from the LRAH panel. This was achieved on August 18 and is believed to be a record high temperature for clean air produced with a heat exchanger while firing coal.
 - Based on inspections by EERC and UTRC personnel, the LRAH panel tiles and support bricks will require replacement before any future test period can be scheduled
 - Inspection of the LRAH tubes indicates that they survived the temperature excursion as a result of the tile release with no obvious damage. The tubes do not appear to have warped. Also, no ash/slag appears to be imbedded in the surface of the tubes.
 - To date, the LRAH panel has been exposed to a range of furnace-firing conditions for a total of 1005 hr. Natural gas firing represents 620 hr and coal–lignite firing represents 385 hr. In addition, the LRAH panel has been exposed to eight heating and cooling cycles and many
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more temperature swings of ± 100 F at temperature. The longest continuous coal-fired period was 80 hr, completed in March 1998.

- Heat recovery data from the LRAH panel for the August test period. Indicate that at cooling air flow rates of 100, 150, 180, and 200 scfm (2.8, 4.2, 5.1, and 5.7 m³/min), the heat recovered from the LRAH panel during coal firing was: 93,550 Btu/hr (98,695 kJ/hr); 97,580 to 101,290 Btu/hr (102,947 to 106,861 kJ/hr); 102,580 to 119,355 Btu/hr (108,222 to 125,920 kJ/hr); and 107,100 to 129,030 Btu/hr (112,990 to 136,127 kJ/hr), respectively.
- In general, the performance of the SRAH panel this past quarter was as anticipated, except for the failure of one of the water-cooled tubes and the loss of a piece of ceramic tile into the bottom of the furnace.
- It has been determined that all of the ceramic tiles and most of the support bricks would require replacement before any future test period could be scheduled using the SRAH panel. Based on the condition of the SRAH panel, the cost to rebuild it, and plans for future use, UTRC has elected not to rebuild the SRAH panel.
- To date, the SRAH panel has been exposed to a range of furnace-firing conditions for a total of 562 hr. Natural gas firing represents 344 hr, and coal/lignite firing represents 218 hr. The longest continuous coal-fired period was 61 hr completed in August. In addition, the SRAH panel has been exposed to three heatup and cooldown cycles.

Investigation continued into the shrinkage problems experienced with the Plicast 99 refractory material. Repeat dilatometer measurements were made to verify the initial tests on the sample of Plicast 99 that contained no organic fibers (which are added to allow steam to escape during firing). These measurements showed the permanent shrinkage ranging from 0.7% to 3.3% as compared to 2.0% to 2.1% for refractory containing organic fibers. The large range of values is possibly due to the sampling method used.

Two blocks of Plicast 99 were subjected to a 40-hr corrosion test at 2732°F (1500°C) in the bench-scale dynamic slagging application furnace, using Coal Creek slag from the first lignite run in the SFS combustor. After two heatup and cooldown cycles, a large expansion crack formed on the back of the refractory block. This reaction along with significant deformation of the samples led to the conclusion that Plicast 99 is not the right material to use with lignite slag.

The performance of the RAH refractories was reviewed along with the furnace history and data that were provided by EERC personnel. Overall, these materials held up quite well in the RAH furnace during numerous thermal cycles and tests, as well as during some unscheduled sudden large temperature fluctuations. While cracks were present in many of the tiles, most of the tiles survived the entire campaign of the 7 LRAH runs. It appears that the slag penetrated the cracks and sealed them, so that they were not a threat to tile life. After the 7th furnace run, which included a high temperature test exposure (tile hot surface approaching 2800°F [1538°C]), the bottom and middle radiation tiles fell out of the LRAH panel during cooling. An examination of the panel indicated that the tiles may have fallen out as a result of the ledge on the bottom panel coming loose.

While there was some reaction of the tiles to the hot flowing slags during the normal RAH furnace runs, the extent of the tile erosion was small. Samples of the Monofrax M and L from the

RAH furnace runs were cut up and analyzed for microstructural changes. Notable differences were observed between the reactions of the two materials with the Illinois No. 6 coal slag. The corrosion effects in the laboratory slag test were more severe, but the types of reactions were consistent with the results observed in the tiles exposed in the RAH furnace.

Task 6 HIPPS Commercial Plant Design Update

The emphasis in the repowering effort is to identify HIPPS power generation cycles using primarily coal with efficiencies comparable to those realized by the Advanced Turbine System (ATS) Program (~60% LHV). Additional work was done on a HAT cycle to identify higher efficiency configurations. Integrating an FT4000 ICAD with more extensive use of ceramic components, a convectively cooled combustor, and some advances in blade cooling into the HIPPS produced a system with an gross efficiency of 56.8% (HHV) or 61.0% (LHV). The net LHV efficiency would be 60.25%., easily comparable to the ATS efficiencies.

Introduction

The High Performance Power Systems (HIPPS) electric power generation plant integrates a combustion gas turbine and heat recovery steam generator (HRSG) combined cycle arrangement with an advanced coal-fired boiler. The unique feature of the HIPPS plant is the partial heating of gas turbine (GT) compressor outlet air using energy released by firing coal in the high temperature advanced furnace (HITAF). The compressed air is additionally heated prior to entering the GT expander section by burning natural gas. Thermal energy in the gas turbine exhaust and in the HITAF flue gas are used in a steam cycle to maximize electric power production. The HIPPS plant arrangement is thus a combination of existing technologies (gas turbine, heat recovery boilers, conventional steam cycle) and new technologies (the HITAF design including the air heaters, and especially the heater located in the radiant section).

The HITAF provides heat to the compressor outlet air using two air heaters, a convective air heater (CAH), and a radiant air heater (RAH). The HITAF is a slagging furnace which contains the radiant air heater, as well as waterwalls and steam drum for the high pressure (HP) steam system. Hot flue gas leaving the HITAF furnace passes over the CAH prior to entering a heat recovery steam generator (HRSG). Hot exhaust gas from the gas turbine is ducted to another HRSG in a typical combined cycle arrangement. The HITAF, gas turbine and HRSGs are configured to achieve the required high efficiency of the HIPPS plant.

The key to the success of the concept is the development of integrated combustor/air heater that will fire a wide range of US coals with minimal natural gas and with the reliability of current coal-fired plants. The compatibility of the slagging combustor with the high temperature radiant air heater is the critical challenge.

Task 2.2 HITAF Air Heaters

Pilot-Scale Testing

EERC activities this past quarter involved design and procurement, construction and shakedown, and HITAF Testing. Final design is complete for all major system components. Other design and procurement activities have been limited to miscellaneous component and equipment items required to improve the performance of the slag tap, slag screen, and system fans; improve temperature measurement in the slagging furnace; and reduce SFS process noise. Design and procurement of miscellaneous component and equipment items are expected to continue through October in support of the procurement and final installation of three optical pyrometers to improve slagging furnace temperature measurement.

The convective air heater (CAH) tube bank was modified in July, and the SFS was operated for nearly 2 weeks this past quarter (August 7–18). Modifications to the CAH tube bank included the addition of fins to the leading and trailing edges of the air-cooled tube surfaces. The slagging furnace operational period involved: planned natural gas firing to cure new refractory in the furnace, slag tap, slag screen, and CAH tube bank; unplanned natural gas-fired periods to facilitate removal of refractory and ceramic tile pieces from the slag tap; and nominally 5 days of Illinois No. 6 bituminous coal firing. Results from the coal-fired test completed in August will be compared in a future topical report with bituminous coal and lignite test results from the two previous quarters. Some of the SFS data and observations for the August coal-fired test period are documented in this report.

The remainder of this section discusses system modifications, observations, and results from the SFS operating period completed in August 1998.

Pilot-Scale SFS

Exhibit 2.2-1 is a simplified illustration of the overall slagging furnace system. This Exhibit was recently updated to correct a piping error and add the mufflers installed to reduce process noise. Equipment procurement activities continued this past quarter on a limited basis and will continue through final installation of the new optical pyrometers for furnace temperature measurement. Procurement this past quarter included five mufflers to reduce SFS process noise and the three optical pyrometers. Electrical work this past quarter included temporary installation of two optical pyrometers for furnace temperature measurement during the August test period and miscellaneous maintenance activities in support of overall system operation.

Exhibit 2.2-1
Combustion 2000 Slagging Furnace and Support Systems

The acquisition of optical pyrometers for furnace temperature measurement was necessary to improve temperature measurement reliability. Temperature measurement in the slagging furnace has been successfully accomplished using Type S thermocouples. However, thermocouple deterioration and subsequent failure were a weekly occurrence. It is not unusual to replace thermocouples after each week of operation. Therefore, in order to improve the reliability of furnace temperature measurement and reduce operating cost, the EERC elected to rent two optical pyrometers for use during the August test period.

The performance of the optical pyrometers compared favorably with the Type S thermocouples during the August test period, meeting performance expectations. Therefore, the EERC has elected to purchase the two optical pyrometers rented for the August test period as well as a third instrument. Two of the optical pyrometers will be mounted in relatively permanent locations to measure furnace flame temperature and flue gas temperature near the ceramic tile surfaces of the LRAH panel. These two instruments will replace two Type S thermocouples. The third optical pyrometer was ordered with fiber optics so that it can be used to measure flue gas and surface temperatures at multiple locations in the furnace and slag screen. Final installation of the optical pyrometers will be completed in October following delivery of the third instrument and refractory work on the slagging furnace.

On the basis of SFS operating experience since the LRAH panel was installed in December 1997, EERC personnel determined that mufflers were necessary to reduce SFS process noise within the high-bay facility and emanating from the stack. The primary sources of noise detected were the induced-draft (ID) fan and the backpressure cooling-air flow control valves supporting the operation of the LRAH panel. The other four fans were found to be secondary sources.

Observations during the August test period indicate that installation of five mufflers has eliminated the higher-frequency noise emitted through the stack. In addition, noise measurements taken during the August test period indicated a noise reduction of 8–9 decibels outside the high-bay structure. Noise levels from the door frame cooling-air fan supporting the radiant air heater (RAH) panels were reduced by fabricating a ventilated box around the fan and by using noise suppression materials. A further reduction in process noise inside the high-bay structure was made in September by repiping a balance air line supporting the coal feed venturi.

Overall reductions in process noise inside the high-bay structure will be determined in November when additional noise measurements will be taken while natural gas is fired in the SFS to cure the refractory. The new data will be compared with data collected during operational periods in 1997 and early 1998.

The modifications, changes, and additions made in May to the SFS to reduce the load on system fans and the overall heat load in the building in which the SFS is located were mostly successful. During the August operating period, the ID fan tripped only when natural gas was fired in an attempt to increase the furnace flue gas temperature near the walls to 3000°F (1649°C) while curing new refractory. Therefore, the maximum flue gas temperature that can be achieved near the walls of the furnace with both RAH panels installed while natural gas is fired is 2900°F (1594°C). Multiple compressor trips caused by reaching high-temperature limits were encountered late one afternoon and early evening during the August test period. However, the nitrogen backup system worked as intended and no real operational problems were encountered. Additional cooling options were implemented in the compressor room during the balance of the August test period, and no additional compressor problems were encountered.

Fuel Feed System

Other than routine maintenance and cleaning, there were no changes or modifications made to the fuel feed system this past quarter. During the August test period (firing Illinois No. 6 bituminous coal) the screw feeder operated effectively at about 30% capacity.

Mechanical seals associated with the screw feeder were replaced in May because of pulverized lignite leaks observed during the test period in April. EERC personnel are uncertain at this time how frequently seal replacement will be necessary. The seals were not replaced prior to the August period, and there are no plans to replace them prior to the next coal-fired test period planned for early December.

Slagging Furnace

The pilot-scale slagging furnace design is intended to be as fuel-flexible as possible, with maximum furnace exit temperatures of 2700° to 2900°F (1483° to 1593°C) to maintain the desired heat transfer to the RAH panels and slag flow. 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 3.2×10^6 kJ/hr) using a single burner. The design is based on a bituminous coal (Illinois No. 6 – 11,100 Btu/lb or 25,800 kJ/kg) and a nominal furnace residence time of 3.5 s. Flue gas flow rates range from roughly 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 a subbituminous coal or lignite increases the flue gas volume, decreasing residence time to roughly 2.6 s. However, the high volatility of the low-rank fuels results in high combustion efficiency (>99%). The EERC oriented the furnace vertically (downfired) and based

the burner design on that of a swirl burner currently used on two EERC pilot-scale pulverized coal- (pc)-fired units that are fired at 600,000 Btu/hr (633,000 kJ/hr). Slagging furnace dimensions are 47 in. (119 cm) inside diameter (i.d.) by roughly 18 ft (5.5 m) in total length. Exhibit 2.2-2 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 four Type S thermocouples protruding <1 in. (<2.5 cm) into the furnace through the refractory wall and more recently using two optical pyrometers. 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.

Observation ports are located in the furnace to permit visual observation of the main burner flame, auxiliary burner flame, RAH panels, slag screen, and slag tap. One sight port is located in the wall of each of the four sections of the slag pot to permit observation of slag buildup and determine when to break up stalagmite-like deposits to make better use of the available volume in the slag pot.

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 repouring refractory. To minimize heat losses, slag is collected in an uncooled, dry container with refractory walls. Because of plugging problems experienced in September and October 1997, the slag tap refractory dimensions were modified, reducing the diameter of the hole to nominally 4 in. (10 cm) and creating a well-defined drip edge. In addition, a multiport natural gas tap burner was added early in 1998. As a result, although some slag tap deposits do form and slag tap erosion is observed, no slag tap plugging was encountered during the SFS operating periods completed in February (Illinois No. 6 bituminous coal), March (Rochelle subbituminous coal), and April (Coal Creek–Falkirk lignite). In June (Center lignite), the slag tap did plug once, likely because of the severe erosion of the entire slag tap. This plug was removed on-line after a switch was made to natural gas firing. In August (with Illinois No. 6 bituminous coal), the slag tap also plugged once as a result of furnace refractory spalling and RAH tile breakage. Again the slag tap opening was cleared on-line after a temporary switch to natural gas firing in the main burner.

Exhibit 2.2-2
Theoretical Flow and Heat-Transfer Data for Combustion 2000 Slagging Furnace and Refractory Ducts - Illinois No. 6 Bituminous

Furnace Firing Rate, kBtu/hr	20 00	25 00	30 00		20 00	25 00	30 00
Furnace				Furnace Exit/Slag Screen			
Furnace i.d., in.	47	47	47	Total Flue Gas Flow,	59	64	66
Furnace Length, ft	16	16	16	Total Flue Gas Flow,	35	39	40
Refract. 1 Thickness,	4	4	4	Furnace Exit Vel., ft/s	33	36	37
Refract. 2 Thickness,	4	4	4	Slag Screen Exit Gas Vel.,	66	72	74
Refract. 3 Thickness,	3.	3.	3.				
Furnace Weight, tons	14	14	14	Dilution Gas			
				Inlet Gas Temp., °F	25	25	25
Inlet Gas Temp., °F	29	30	31	Gas Velocity in, ft/s	61	67	69
Avg. Gas Temp., °F	28	28	29	Exit Gas Temp., °F	18	18	18
Exit Gas Temp., °F	27	27	27	Dilution Gas Temp., °F	30	30	30
Refract. 1 Surf. Temp.,	26	27	27	Dilution Gas Flow, scfm	24	28	28
Refract. 2 Surf. Temp.,	24	24	25	Total Flue Gas Flow,	84	92	95
Refract. 3 Surf. Temp.,	17	17	18	Flue Gas Flow Rate out,	37	41	42
Furnace Skin Temp., °F	27	27	28	Gas Velocity out, ft/s	67	74	76
Coal Feed Rate, lb/hr	17	22	26	Dilution Gas Nozzles			
Airflow Rate, scfm	39	49	59	Nozzle Diameter, in.	1.	1.	1.
Flue Gas Flow Rate,	42	53	64	No. of Nozzles	8	8	8
Flue Gas Flow Rate,	26	34	41	Dilution Gas Flow, acfm	36	40	42
Furnace Gas Velocity,	3.	4.	5.	Dilution Gas Velocity,	89	10	10
Flue Gas Residence	4.	3.	2.				
				Convective Air Heater			
Auxiliary Burner, scfm	16	11	20	Gas Temp., °F	18	18	18
Auxiliary Burner,	89	56	11	Flue Gas Flow Rate,	36	40	41
Total Firing Rate,	28	30	31	Gas Velocity, ft/s	52	57	59
Wall Losses, kBtu/hr	19	20	20				
RAH Losses, kBtu/hr	19	19	19				

Assumption: Excess air is 20%.

The refractory walls in the slagging furnace are composed of three layers of castable. They consist of: an inner 4-in. (10.2-cm) layer of high-density (14-Btu-in./ft²-°F-hr or 2.0-W/m-K) slag-resistant material, 4 in. (10.2 cm); an intermediate refractory (4.0 Btu-in./ft²-°F-hr or 0.6 W/m-K), and a 3.25-in. (8.3-cm) outer layer 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 keep the overall size and weight of the system to a minimum while reducing slag corrosion and heat loss. Because of its greater structural strength and high corrosion resistance, Plibrico Plicast Cement-

Free 98V KK alumina castable was originally used as the inner layer in the top three furnace sections, in the exit of the furnace, and in the top section of the dilution/quench zone. Plicast Cement-Free 99V KK was used in the bottom furnace section (except for the exit), slag tap, slag screen, and transition to the dilution/quench zone because of its even greater resistance to slag attack.

After several weeks of furnace operation, refractory repairs were made to the high-density refractory in the top section of the furnace and the upper middle furnace section. In the top section of the furnace, the Plibrico Plicast Cement-Free 98V KK refractory was replaced with a Narco Cast 60 castable refractory. Replacement was necessary because of the shrinkage found in the Plibrico Plicast Cement-Free 98V KK. The Narco Cast 60 refractory was selected as a replacement because of past success with its use in other furnace systems. Although the Narco Cast 60 is much more prone to slag corrosion, operating experience with bituminous and subbituminous coal had shown that slag deposition was not significant in the top section of the furnace. After over 6 weeks of operation, the Narco Cast 60 refractory appears to be in good shape, although refractory deterioration was evident in the top section of the furnace after 2 weeks of lignite firing. Therefore, the high-density refractory in the top section of the furnace will be 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 previously used in this section of the furnace.

The upper middle section of the furnace showed more severe refractory damage as a result of lignite firing. Some patching of the high-density refractory in the upper middle furnace section was necessary after the test periods completed in April and June, especially where the refractory was itself a fresh patch. EERC personnel believe that the newly repaired/patched portions of the refractory corroded excessively because it was not fired to as high a temperature as the older refractory had been during the original system shakedown before coal– lignite feed was begun. As part of the August test period, the EERC attempted to cure the new refractory at 2900° to 3000°F (1594° to 1649°C) in order to improve its corrosion resistance. However, using natural gas with both RAH panels installed limited maximum furnace temperatures to 2850°F (1566°C).

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. The refractory lasted until after the August test period, after which the decision was made to replace it because of extensive cracking caused by the differences in the expansion and contraction of the inner and middle liners during a run. Actual corrosion of the inner liner was minimal, except for newer patches that were not completely sintered and for areas of flame impingement. The timing works out well with the need to replace/reassemble ceramic components in the LRAH panel. Exhibit 2.2-3 summarizes properties for refractories used in the SFS.

Exhibit 2.2-3 Refractory Properties

Refractory:	Function	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
		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.

Main and Auxiliary Burners

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 that 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 conversion has been >99% when bituminous and subbituminous coal and lignite are fired. High carbon conversions can be obtained 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 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. Use of the auxiliary gas burner is beneficial during start-up to reduce heatup time and to prevent slag from freezing on the slag screen when the switch is initially made to coal firing.

Radiant Air Heater Panels

The LRAH test panel arrived at the EERC on September 15, 1997. Final assembly and installation of the LRAH panel into the furnace took place in November 1997. A key design feature of the furnace is accessibility for installation and testing of one LRAH panel and one SRAH panel. The furnace design will accept one 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.

Cooling air for the LRAH panel is provided by an existing EERC air compressor system having a maximum delivery rate of 510 scfm (14.4 m³/min) and a maximum stable delivery pressure of 275 psig (19 bar). Backup cooling air is available from a smaller compressor at a maximum delivery rate of 300 scfm (8.5 m³/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. In the event of a failure of inlet cooling air piping, a backflow emergency piping system was installed so that overheating of the LRAH panel could be avoided. UTRC designed and fabricated the RAH test panels.

Furnace design also permits the installation of a smaller 1.5 - 5.4-ft (0.46- 1.65-m) RAH panel. The purpose of the SRAH panel is to expose cooled ceramic materials to slagging furnace conditions rather than to generate heat-transfer data. A primary difference between the LRAH and SRAH panels is that the SRAH panel is 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 (OD) 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 used 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 was delivered the first week of April and installed prior to the weeklong lignite test period completed

April 19–24. Shakedown and initial testing of the SRAH panel were completed in April 1998. As result of damage sustained by the SRAH panel during the August test period, the panel has been removed from the slagging furnace. UTRC personnel have determined that rebuilding the SRAH panel is not warranted and that further materials testing can be accomplished using the LRAH panel. Therefore, the area of the slagging furnace in which the SRAH panel was located will be filled in with insulating, intermediate, and high-density refractory as part of the high-density refractory replacement activity.

Slag Screen

The slag screen design for the pilot-scale slagging furnace system is the result of a cooperative effort between the EERC, UTRC, and 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 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 mm Hg); and
- 5) limiting heat losses to assure desired slag flow from the slag screen to the furnace slag tap.

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 Exhibit 2.2-3. Water-cooled surfaces were installed inside of the refractory tubes to cool the tubes and reduce the erosion/corrosion observed during shakedown tests. Specific details concerning slag screen modifications and performance this past quarter are addressed later in this report.

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 and maintains a 1.17-ft (0.36-m) diameter in the area of the flue gas recirculation nozzles, with the duct diameter expanding to 2 ft (0.6 m) to provide adequate residence time within duct length constraints. The duct section containing the flue gas recirculation nozzles is a spool piece to accommodate potential changes to the size, number, and orientation of the flue gas recirculation 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 has been required during each weeklong bituminous and subbituminous coal test period. In order to better monitor and document the slag deposition in the dilution/quench zone, a differential pressure transmitter was purchased and installed in April 1998. Based on observations during the August test period and the frequent

cleaning required, the EERC plans to modify the spool piece section of the dilution/quench. The specific modifications will involve the addition of a water-cooled wall around the flue gas recirculation nozzles. This water-cooled wall should embrittle the slag deposits that form in this area, making them easier to remove on-line.

Convective Air Heater

The CAH design was a cooperative effort between the EERC and UTRC. It was constructed by UTRC and installed in September 1997. The flue gas flow rate to the CAH tube bank has been calculated to range from 3553 to 4619 acfm at 1800°F (101 to 131 m³/min at 982°C). 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. The CAH 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 are 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 they were repeatedly damaged when the tube bank was removed from the duct after the test periods in February, March, and April.

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). Exhibit 2.2-4 illustrates the position, size, and alloy type for the five uncooled tubes. The five uncooled tubes are arranged such that the first two tubes in the flue gas path are the 0.75-in. (1.9-cm) Schedule 40 PM2000 material. The third tube is the 1-in. (2.5-cm) Schedule 40 Incoloy MA956HT material, and the last two tubes are the 1.5-in. (3.8-cm) Schedule 80 Incoloy MA956 material. Exhibit 2.2-5 is a photograph of the CAH tube bank with the new uncooled tubes installed.

Exhibit 2.2-4
Illustration of the New Uncooled Tubes installed in the CAH Tube Bank

Exhibit 2.2-5
Photograph of the New Uncooled Tubes Installed in the CAH Tube Bank

Heat is recovered from the flue gas to meet cooling air temperature requirements for the CAH. The design cooling air exit temperature from the CAH is 1200°F (649°C) and is not permitted to exceed 1300°F (705°C). The cooling air exit temperature is controlled by varying the airflow rate with a control valve.

System Fans

The SFS has five fans - a combustion air forced-draft (FD) fan, two cooling-air (CA) FD fans, an ID fan, and a flue gas recirculation (FGR) fan. Exhibit 2.2-6 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.

**Exhibit 2.2-6
Pressure, Temperature, and Flow Specifications for 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
CA Fan	0	1.5	60	20	100	1200	1292	1200	20
ID Fan	1	0.5	350	250	450	1200	2255	1755	25
FGR Fan	0	1.5	350	250	450	450	788	701	10
CA Fan	0	2.0	80	60	100	200	200	200	5

Emission Control

A pulse-jet baghouse is used for final particulate control on the pilot-scale 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 15 in. W.C. (28 mm Hg).

Total flue gas flow rate downstream of the baghouse is measured using a venturi. Flue gas sample ports were installed in the inlet and outlet piping of the baghouse to permit flue gas sampling for gaseous/vapor-phase constituents as well as fly ash. Fly ash particle-size distribution and mass loading are determined periodically using standard U.S. Environmental Protection Agency (EPA) methods. Hazardous air pollutant (HAP) measurements can be taken through existing sample ports using EPA Method 29 and the Ontario Hydro method for mercury speciation.

Instrumentation and Data Acquisition

The instrumentation and data acquisition components for the pilot-scale SFS address combustion air, flue gas, cooling air, cooling 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, carbon dioxide, 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 reaching the analyzers. Flue gas is routinely sampled in the slag screen at the furnace exit and the exit of the baghouse.

The only instrumentation work completed this past quarter, with the exception of routine maintenance, was the temporary installation of two optical pyrometers for furnace temperature measurement.

Pilot-Scale SFS Operation

The pilot-scale SFS was fired on gas and Illinois No. 6 coal during the period August 7–18. The purpose of the August test period was to further evaluate the SRAH and LRAH panels while firing bituminous coal in the SFS at 100% load and to try to achieve an air temperature of 2000°F (1093°C) at the LRAH outlet. Initial data evaluation and some of the sample analysis have been completed. Therefore, this report summarizes available results and observations for the August test period as well as SFS maintenance and modification activities.

Fuel Feed System

The fuel feed system was operated in August for 116 hr with Illinois No. 6 coal at nominal feed rates of 190 to 200 lb/hr (86 to 91 kg/hr) in an attempt to maintain a flue gas temperature near the RAH tile surfaces of 2800°F (1538°C). Specific tests were also completed at coal feed rates of 180 and 210 lb/hr (82 and 95 kg/hr). Exhibit 2.2-7 illustrates the coal feed rate for the test. During the test, the coal feed rate was quite stable except for a few spikes (high and low) associated with coal hopper refill cycles.

Exhibit 2.2-7
Coal Feed Rate Versus Run Time for the August 1998 Test Period

Exhibits 2.2-8 and 2.2-9 summarize analytical results for the Illinois No. 6 bituminous and Rochelle subbituminous coal and the Coal Creek–Falkirk and Center lignites, respectively, that have been fired in the pilot-scale slagging furnace. For the August test period, the Illinois No. 6 coal analyses indicated that the as-fired fuel contained 5.1–5.3 wt% moisture, 11.1–11.3 wt% ash, and 3.3–3.4 wt% sulfur. The heating value was 11,169–11,407 Btu/lb (25,994–26,549 kJ/kg) on an as-fired basis. Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2342°F (1284°C) and a fluid temperature of 2515°F (1380°C). Dry-sieve analysis indicated that the pulverized Illinois No. 6 coal was nominally 80–82 wt% for 200 mesh (74 microns).

X-ray fluorescence (XRF) analysis results for the various fuels are summarized in Exhibits 2.2-8 and 2.2-9 and reported as oxides. However, these data for the Illinois No. 6 coal, slag, and ash samples resulting from the August test period were not available for inclusion in this report.

Exhibit 2.2-8
Results of Coal and Coal Ash Analysis for Coal-Fired Slagging Furnace Tests ¹

	Illinois No. 6 Bituminous Coal	Rochelle Subbituminous Coal
Proximate Analysis, wt%		
Moisture	4.8–10.3	21.6–24.3
Volatile Matter	35.9–37.8	35.6–37.4
Fixed Carbon	43.3–46.3	35.8–36.7
Ash	10.6–11.2	4.3–4.7
Ultimate Analysis, wt%		
Hydrogen	4.9–5.8	6.1–6.4
Carbon	61.6–64.9	53.0–55.2
Nitrogen	0.8–1.1	0.6–0.7
Sulfur	3.2–3.5	0.3–0.3
Oxygen	14.7–17.6	32.9–33.4
Ash	10.6–11.2	4.3–4.7
Heating Value, Btu/lb	11,036–11,658	9021–9328
Percent as Oxides, wt%		
SiO ₂	52.8–53.9	26.7–27.1
Al ₂ O ₃	20.6–21.2	15.5–16.3
Fe ₂ O ₃	13.6–14.3	6.3–6.6
TiO ₂	0.9	1.2–1.4
P ₂ O ₅	0.1–0.2	0.7–0.9
CaO	3.2–3.5	21.6–24.3
MgO	1.5–1.6	6.7–6.9
Na ₂ O	1.1	1.5
K ₂ O	1.9–2.1	0.1–0.4
SO ₃	2.5–2.7	15.6–17.0
Ash Fusion Temp., °F		
Initial	2315–2361	2202–2295
Softening	2342–2377	2205–2308
Hemisphere	2392–2439	2214–2311
Fluid	2505–2534	2221–2325
Sieve Analysis		
Screen Mesh Size	Weight Percent Retained	
100	1.8–6.2	7.6–8.8
140	0–11.2	14.2–15.4
170	0–14.9	NA ²
200	9.6–13.5	14.3–14.4
230	0–16.2	8.4–9.1
270	4.2–14.6	2.0–5.6
325	7.4–11.8	4.8–11.6
400	0–4.7	NA
Pan	41.6–57.8	39.7–43.4
Total %	99–100.2	98.6–100.6

¹ Coal analysis is presented on an as-fired basis.

² Not available.

Exhibit 2.2-9
Results of Lignite and Lignite Ash Analysis for Lignite-Fired
Slagging Furnace Tests ¹

	Coal Creek–Falkirk Lignite	Center 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	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	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 ²	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 applicable.

Slagging Furnace Operation

The slagging furnace heating rate during the August test period was limited to 50°F/hr (28°C/hr) while natural gas was fired. The slow rate was necessary to cure new refractory in the furnace, slag screen, and CAH. When the furnace reached normal operating temperature (2800°F/1538°C), the main burner natural gas-firing rate was maintained at 2.3 to 2.4 MMBtu/hr (2.4 to 2.5 x 10⁶ kJ/hr) for about 12 hr, with an auxiliary burner firing rate of 0.8 MMBtu/hr (0.9 x 10⁶ kJ/hr). Subsequently, the main burner natural gas-firing rate was increased to 2.8 MMBtu/hr (2.9 x 10⁶ kJ/hr) in an attempt to further cure/sinter the new refractory in the furnace and slag screen. However, at a main burner natural gas-firing rate of 2.8 MMBtu/hr (2.9 x 10⁶ kJ/hr) the ID fan tripped, forcing EERC personnel to reduce the firing rate. The main burner natural gas-firing rate was maintained at 2.5 to 2.8 MMBtu/hr (2.6 to 2.9 x 10⁶ kJ/hr) for 12 hr in order to adequately cure/sinter the new high-density refractory. The maximum flue gas temperature achieved and maintained near the furnace walls was 2850°F (1566°C). Before the switch to coal firing in the main burner, the natural gas-firing rate was reduced to 2.2 MMBtu/hr (2.3 x 10⁶ kJ/hr) in order to stabilize the furnace flue gas temperature near the RAH panels at 2800°F (1538°C). A summary of furnace and slag screen temperatures is presented as a function of run time in Exhibit 2.2-10 for the August RAH panel tests. Corresponding slagging furnace firing rate data are summarized in Exhibit 2.2-11.

Exhibit 2.2-10
Furnace and Slag Screen Temperatures Versus Run Time for the August 1998
Test Period

Exhibit 2.2-11
Slagging Furnace Firing Rate Versus Run Time for the August 1998 Test Period

During the period of August 13–18, the furnace was fired on Illinois No. 6 bituminous coal at 100% load. Once furnace refractory curing was completed, the total furnace-firing rate (main plus auxiliary burners) ranged from 2.8 to 3.2 MMBtu/hr (2.9 to 3.3×10^6 kJ/hr). Prior to installation of the SRAH panel, total furnace firing rates exceeding 3 MMBtu/hr (3.1×10^6 kJ/hr) occurred only during natural gas-fired tests. However, with the SRAH panel installed, it was necessary to increase the firing rate of the main and auxiliary burners to maintain nominal furnace temperatures of 2700° to 2800°F (1483° to 1538°C). A series of coal-fired tests was performed at main burner firing rates of 2.1 to 2.4 MMBtu/hr (2.2 to 2.5×10^6 kJ/hr). The main burner accounted for 75% of the total energy input.

During the August test period, EERC personnel attempted to maximize the main burner firing rate and minimize the auxiliary burner firing rates, while controlling the furnace temperature at 2800°F (1538°C). However, it was necessary to maintain a minimum auxiliary burner firing rate of 0.75 MMBtu/hr (0.8×10^6 kJ/hr) to maintain adequate slag screen and slag tap temperatures and slag flow.

Once furnace temperatures were stable, the duration of individual test periods ranged from 2 to 6 hr. Two natural gas-fired and thirteen coal-fired test periods were completed. At 100% load, furnace temperature was controlled at nominally 2800°F (1538°C), depending on total furnace firing rate, main burner firing rate, and main burner swirl settings. Furnace refractory temperatures ranged from 1150° to 1350°F (621° to 732°C) for the hot side of the insulating refractory to as high as 2670°F (1466°C) for the cold side of the high-density refractory. Compared to previous test periods with the Illinois No. 6 and Rochelle coals, insulating and high-density refractory

temperatures were 15° to 30°F (8° to 17°C) lower. However, it was necessary to increase the total furnace firing rate in August to offset furnace heat losses to the SRAH panel. A comparison with lignite test periods at the same firing rate indicates that the insulating and high-density refractory temperatures were 100°F (56°C) higher during the August test period with Illinois No. 6 coal. The higher refractory temperatures observed during the Illinois No. 6 coal-fired test periods are believed to be the result of higher flame temperatures due to the lower Illinois No. 6 moisture content.

Operating problems encountered during the August test period were related to high-density furnace refractory, RAH panel tiles, and slag screen-dilution/quench zone performance. Slag screen-dilution/quench zone observations will be addressed later in this report. Prior to initiating coal feed, it was necessary to remove the slag pot from the bottom of the combustor to facilitate the removal of a piece of high-density furnace refractory from the slag tap. The piece of refractory was large enough to bridge the slag tap opening. It apparently spalled from the high-density refractory layer in the furnace. Although removal of the slag pot delayed the initiation of coal feed, SFS operation was not affected.

Once coal feed was initiated, it continued for about 61 hr, at which time a water tube leak in the SRAH panel forced a temporary termination of coal firing and a reduced natural gas-firing rate. Once the water to the damaged tube was shut off, a piece of ceramic tile was observed in the slag tap. Again the slag pot was removed, and the piece of ceramic tile was recovered from the slag tap along with a second piece of refractory. Roughly 8 hr were lost as a result these activities and the subsequent reheating of the slagging furnace on natural gas prior to the resumption of coal firing.

Once coal feed resumed, it continued for about 55 hr. At that time, failure of the two large lower tiles on the LRAH panel forced the SFS operation to terminate. Over the course of 116 hr of coal firing during the August test period, the slag tap never plugged and slag flow was not a problem. Removal of pieces of refractory and ceramic tile that were observed bridging the slag tap was necessary to avoid potential plugging problems. The refractory in the slag tap was replaced before the August operating period to repair slag corrosion damage that occurred as a result of the lignite-fired test period completed in June.

Minor pressure surges (a few inches of W.C.) observed during the August test period are not uncommon in the slagging furnace. They happen on a periodic basis as a result of baghouse cleaning, opening access ports to clean the dilution/quench zone and CAH tube bank, opening 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 August test period.

Inspection of the furnace refractory after the August test indicated further deterioration of the high-density layer in specific areas of the furnace. Refractory deterioration was less severe compared to that observed after the lignite-fired test periods in April and June. However, it has been decided to replace the high-density refractory layer before the next SFS test because the layer has cracked and because repairs are also being made to the LRAH, so it would be a good time to better match the opening in the refractory to the panel. As of the end of September, the high-density refractory layer has been removed from the furnace and the refractory in the top

furnace section has been repoured. Depths of slag penetration into the layer are reported in the section of this report describing the laboratory and bench-scale research.

Main and Auxiliary Burners

The main and auxiliary burners performed well during the August test. Main burner swirl adjustment was more than adequate to establish a stable flame when the Illinois No. 6 coal was fired. The EERC evaluated main burner swirl settings on LRAH and SRAH panel performance at minimum, moderate, and maximum swirl settings. Adjustments to swirl setting had no effect on carbon efficiency because of the high furnace operating temperature. At this time, the EERC suggests that the slagging furnace be operated using minimum-to-moderate primary 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. Sufficient data are already available to evaluate the effect of primary burner swirl on RAH panel heat transfer; therefore, future RAH panel test periods could exclude adjustments to primary burner swirl as a parameter.

Slag Screen

Slag screen flue gas temperatures during the August test period were typically 2600° to 2700°F (1427° to 1482°C) at the inlet and 2575° to 2675°F (1413° to 1469°C) at the outlet, respectively. Slag screen operating temperature is selected based on 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 August test period was determined to be 2515°F (1380°C). A composite slag sample collected from the slag pot was found to have a fluid temperature of 2688°F (1476°C).

Exhibit 2.2-12 presents a photograph of the outlet (bottom) of the slag screen following the August test. The high-density refractory was in good condition. Some limited water cooling of the slag screen floor and the floor of the furnace exit was installed prior to the August test period to better protect the refractory in these areas from the attack experienced previously. Inspection of the top and bottom of the slag screen following the August test period indicated that the additional cooling significantly reduced slag penetration and erosion/corrosion of the high-density refractory. However, the first two rows of tubes had been lost to a combination of inadequate water flow rate and a water leak. The first two rows of tubes visible from the inlet side show signs of erosion/corrosion, while the tubes visible from the outlet side appear to have a uniform layer of slag on the surface.

Exhibit 2.2-12
Photograph of Slag Screen Tubes Following the August 1998 Test Period

The failure of the first two rows of tubes resulted in the formation of a dam that prevented the slag from flowing freely down to the slag tap. As a result, a pool of slag developed in the slag screen. The pool reduced the cross-sectional area of the duct, increasing the flue gas velocity and slag screen differential pressure. The operating conditions stabilized when the level of the slag pool reached a point at which the slag began to flow into the dilution/quench zone. 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. (6 to 14 mm Hg). Normally the slag screen differential pressure is 2 in. W.C. (4 mm Hg). A slag sample collected from the slag pool was found to have a fluid temperature of 2543°F (1395°C). The material found to have effectively dammed the slag screen had ash fusion temperatures that all exceeded 2800°F (1538°C).

Although the slag screen refractory was in good shape, the high-density refractory was damaged as a result of removing the slag pool during maintenance. Therefore, it will be necessary to partially rebuild the slag screen prior to the next test period. Specifically, the tubes and the high-density refractory will be replaced. One change EERC personnel plan to make is to reduce the size of the water-cooled stainless steel tubes in the slag screen. During the lignite-fired tests, more cooling was necessary to build up a sufficiently thick 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 18 refractory slag screen tubes was increased for lignite testing. However, when Illinois No. 6 coal was fired, the 0.375-in.-(0.952-cm)-OD water-cooled

stainless steel tubes appeared to provide too much cooling, forcing higher auxiliary burner firing rates to maintain slag screen temperatures and desired slag flow. Therefore, the size of the stainless steel tubes will be reduced to 0.25 in. (0.63 cm) OD. This tube size should be appropriate for the Illinois No. 6 coal. The tube size will have to be reevaluated in the future when other fuel types are considered. The slag screen tubes will likely always require periodic replacement based on some level of erosion/corrosion and the fuels selected for testing.

Following the August 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 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 August test was 82%. Slag recovery from the furnace, slag pot, and dilution/quench zone represented nominally 72% of the theoretical ash. Additional slag is evident on the furnace wall, 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 represents at least 5% of the theoretical ash. Also, it is not possible to determine what fraction of the recovered slag is actually refractory from the furnace or slag screen. Collected material and these estimates indicate that over 75% of the coal ash was captured in the system as slag. The 82% closure on ash and slag for the August Illinois No. 6 test period was lower than that for the February Illinois No. 6 test period (95%) but comparable to results with the Rochelle subbituminous coal (85%) and the Coal Creek-Falkirk lignite (80%).

Fly ash recovered from other system components (drawdown gas line, CAH duct, CA preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping) represented roughly 10% of the theoretical ash. Nominally 10% to 15% of the ash in the fuels fired in the SFS has reaching the baghouse. However, the baghouse ash recovered following the August test period represented only 5% of the total ash/slag. Mass balances will be completed for all future test periods to further document the distribution of slag and ash in the system.

Dilution/Quench Zone

During the August 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-line every hour. Occasionally cleaning was required on a 30- or 90-minute basis. The amount of slag entering the dilution/quench zone was illustrated by the fact that 34% of the ash/slag recovered from the SFS was recovered in the dilution/quench zone. Material recovered from the dilution/quench zone during previous Illinois No. 6 test periods was typically <13%. Downstream of the FGR nozzles, the small quantity of ash observed on the refractory walls was weakly sintered.

CA Preheaters

During the August test period, the cooling air for the CAH tube bank and the LRAH panel was heated using air preheater tube bundles located downstream of the CAH. Further heating of the cooling air entering the LRAH panel was achieved electrically and by recovering heat from the CAH tube bank. Cooling air for the CAH tube bank is supplied by the first cooling air preheater tube bundle. During the August test, cooling air entering the CAH tube bank was controlled at set points ranging from 1020° to 1120°F (549° to 605°C) for nominal cooling air flow rates of 100 to

115 scfm (1.8 to 3.3 m³/min). During a high-temperature LRAH panel test, cooling air entering the CAH tube bank was allowed to approach 1220°F (660°C) for a nominal cooling air flow rate of 85 scfm (2.4 m³/min). Cooling air temperatures at the exits of the other four preheater tube bundles were nominally 1240° to 1340°F (671° to 727°C) for flow rates totaling 100 to 150 scfm (2.8 to 4.2 m³/min).

Cooling air preheater temperatures are shown as a function of run time in Exhibit 2.2-13. The temperature spike to a high level just prior to the termination of coal firing was the result of imbalanced cooling air flow through the four tube bundles. Although the cooling air preheater heat-transfer rate degraded with time as ash deposits developed on the tube surfaces, cooling air temperature and flow rate control were adequate to support operation of the CAH tube bank and the LRAH panel. Therefore, additional heaters are not necessary at this time to achieve operational objectives with bituminous and subbituminous coal.

Exhibit 2.2-13
Cooling Air Preheater Temperatures Versus Run Time for the August Test Period

Emission Control

During gas- and coal-fired furnace operation in August, baghouse temperatures and temperature profiles looked good, and the electrical heaters worked well, limiting the potential for condensation on start-up and shutdown. However, the water tube leak in the SRAH panel did result in acid condensation on some piping surfaces and uninsulated surfaces in the back end of the SFS. Because the baghouse walls are heated, no acid condensation was observed in the baghouse. Measured inlet and outlet particulate mass loadings were nominally 0.07 gr/scf (160

mg/Nm³) and 0.0006 gr/scf (1.37 mg/Nm³), respectively, resulting in a particulate collection efficiency of roughly 99.1% when the Illinois No. 6 bituminous coal was fired in August.

The measured inlet particulate loadings are roughly 70% lower than what was measured previously when the Illinois No. 6 bituminous coal was fired, as well as the subbituminous coal and lignites. 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 - which may have increased the slag screen particulate collection efficiency. Particulate sampling data from the next Illinois No. 6 coal-fired test period should assist in determining the cause of the reduced baghouse inlet mass loading. Calculated particulate emissions from the pulse-jet baghouse were 0.0024 lb/MMBtu. This is comparable to other tests of Illinois No. 6 bituminous coal.

Removal of the bags from the baghouse for cleaning following the August test period was more difficult than normal. The bags appeared to have shrunk, making cage removal difficult. Inspection during the cleaning process revealed the presence of small holes and tears in several of the bags. These were observed near the bottom of the bags where cage vertical wire impressions were apparent on the bag surface. Examples of the failed bags have been shipped to the bag vendor for evaluation. One possible explanation may be the water tube leak in the SRAH panel. The increased water content of the flue gas and the higher acid and moisture dew points may have resulted in bag shrinkage, even though baghouse temperatures were typically 350° to 380°F (177° to 194°C) and never less than 320°F (160°C). Shrinkage would explain the difficulty encountered with cage removal during maintenance and the bag holes/tears could have been the result. This scenario is also consistent with the low baghouse particulate emissions observed. EERC personnel will discuss replacement bag options with the vendor, along with an interpretation of possible bag failure scenarios. A new set of bags will have to be purchased and installed prior to the next coal-fired test period.

Particle size analysis was completed for a composite ash sample collected from the baghouse hopper. The data show the ash to be 100 wt% <18 microns, 80 wt% <8 microns, and 50 wt% <5 microns. Multicyclone sampling was planned for the August test period, but not completed because of the forced shutdown. Therefore, multicyclone data are not available for comparison with the ash particle size data. Multicyclone sampling will be completed during the next coal-fired test period.

Analysis of the baghouse ash was also completed for carbon content as measure of combustion efficiency. The carbon content of the baghouse ash was found to be 0.29 wt%, indicating a high combustion efficiency consistent with the high operating temperature of the slagging furnace.

Exhibit 2.2-14 shows the average gaseous emissions measured during the August test. Data from a February test period are included for comparison. The data are based on furnace exit measurements made in the slag screen outlet. The carbon monoxide (CO) concentration of 80 ppm is a direct result of firing the main burner at a low swirl setting and a higher-than-average coal feed rate. Typical CO concentrations were 10 to 40 ppm. Main burner swirl setting was observed to have an effect on CO concentrations. At a burner swirl setting of 25%, the CO concentration was 40 ppm or less. When burner swirl was increased to 50%, the CO concentration was 20 ppm or less.

Total nitrogen dioxide emissions were determined to range from 0.92 to 1.34 lb/MMBtu. Nitrogen dioxide emissions were higher during individual test periods, represented by higher average coal feed rates and higher main burner swirl settings. 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.

No attempt at controlling sulfur emissions was made. Calculated sulfur dioxide emissions were 5.8 to 6.2 lb/MMBtu and based on only the main burner firing rate.

Exhibit 2.2-14
Flue Gas Emissions for Illinois No. 6 Coal-Fired Slagging Furnace Tests

	Concentration	lb/MMBtu
August		
O ₂	3.5%–4.5%	
CO ₂	12.9%–14.3%	
CO	10–80 ppm	
NO _x	380–540 ppm	0.9–1.3
SO ₂	2370–2800 ppm	5.8–6.2
February		
O ₂	4.0%–5.0%	
CO ₂	12.6%–14.0%	
CO	5–50 ppm	
NO _x	360–600 ppm	1.0–1.4
SO ₂	2280–3140 ppm	5.6–6.1

Testing of the CAH Tube Bank

The CAH tube bank was installed and initially evaluated during a shakedown test completed in October 1997. Cooling air flow was adequate for temperature control and to evaluate the performance of the CAH tube bank during the August test period. Exhibits 2.2-15 through 2.2-17 summarize CAH tube bank surface and flue gas temperatures, cooling air temperatures, and cooling air flow rate data for the August test period. Exhibit 2.2-18 illustrates the location of thermocouples in the CAH tube bank, and Exhibit 2.2-19 presents a list of thermocouple descriptions.

Exhibit 2.2-15
CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the August Test Period

Exhibit 2.2-16
CAH Cooling Air, LRAH Cooling Air, Quench Gas, and Flue Gas Flow Rates Versus Run Time for the August Test Period

Exhibit 2.2-17
CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the August Test Period

Exhibit 2.2-18
Thermocouple Locations in the CAH Tube Bank

Exhibit 2.2-19
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
	12	CAHIT2	5 in. up center tube, facing upstream
	13	CAHIT3	8 in. up center tube, facing upstream (failed prior to August test period)
	14	CAHIT4	5 in. up center tube, facing to side
	15	CAHIT5	5 in. up center tube, facing downstream
Header Shell	16	CAHTC4	Next to shell on outside, between return air pipes

¹ Thermocouple locations are illustrated in Exhibit 2.2-18.

Prior to the August 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. No other CAH thermocouples were damaged during the test.

While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 40,000 to 45,000 Btu/hr (42,200 to 47,475 kJ/hr). The cooling air flow rate was 120 to 135 scfm (3.4 to 3.8 m³/min). The inlet cooling air was 1110° to 1200°F (599° to 649°C), outlet cooling air was 1360° to 1390°F (738° to 755°C), and flue gas was 1790° to 1830°F (977° to 999°C) entering the CAH tube bank. Exhibit 2.2-20 presents heat recovery in the CAH as a function of run time for the August test.

Exhibit 2.2-20
CAH Heat Recovery Versus Run Time for the August Test Period

When coal firing (Illinois No. 6) began, surface temperatures initially decreased at a rate of nominally 15°F/hr (8°C/hr) over nearly 7 hr as ash deposits developed on the surface of the tubes. After nearly 30 hr of coal firing, that rate dropped to about 2°F/hr (1°C/hr). It must be noted that cooling air flow rates were also decreasing (0.4 scfm/0.01 m³/min) over these time frames in an attempt to maintain a relatively constant cooling air exit temperature. The minimum cooling air flow rate through the CAH tube bank was 85 scfm (2.4 m³/min). Relatively stable temperatures were observed during natural gas-fired periods prior to initiating coal feed at about Run Hour 82 and during the coal feed period between Run Hours 109 and 193. As ash deposits developed on the tube surfaces, heat recovery from the CAH tube bank decreased from roughly 40,000 Btu/hr (42,200 kJ/hr) to 26,800 Btu/hr (28,274 kJ/hr). Heat recovery from the CAH tube bank remained at this level for nearly 30 hr of coal firing before further degradation was observed. Over the last 37 hr of coal firing, heat recovery degraded from 26,800 to 16,700 Btu/hr (28,274 to 17,618 kJ/hr).

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. Further testing will be necessary to verify these data.

EERC personnel did not attempt to clean the CAH tube bank during the August test to facilitate the development of ash deposits for characterization. If CAH tube bank cleaning had occurred, heat recovery would have been expected to improve by 10,000 to 15,000 Btu/hr (10,550 to 15,825 kJ/hr) and then decreased to a level approaching 15,000 Btu/hr (15,825 kJ/hr). CAH tube bank plugging was not a problem. 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. Previous tests with the Illinois No. 6 coal had not resulted in any complete bridging between tubes. No deposits were observed bridging the flue gas paths between the tubes.

Exhibit 2.2-21 presents a photograph of ash deposits on the surface of the air-cooled tubes following the August test. The photograph shows the air-cooled tubes following removal from the duct. The complete bridging of ash deposits between the leading and trailing edges of tubes is evident. The pieces of tube deposit missing from the photograph of the air-cooled tubes are still attached to the uncooled tubes in the duct. The leading- and trailing-edge of the five stainless steel tubes in the duct immediately upstream of the air-cooled tubes also displayed ash deposits, and the stainless steel tubes showed severe surface oxidation as a function of flue gas exposure.

Exhibit 2.2-21
Photographs of Ash Deposits on the CAH Tubes Following the August Test Period
Firing Illinois No. 6 Bituminous Coal

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 remained intact when

the CAH tube bank was removed from the duct. Also, the deposits were generally removed intact from the tube surfaces. The total weight of the deposits collected from the CAH tubes and duct was 48 lb (21.8 kg). The total weight of the deposits collected from the CAH tubes was 11 lb (5 kg). An ash deposition rate can be expressed in many ways for the CAH tube bank. On a mass per unit time basis, the ash deposition rate for this Illinois No. 6 coal-fired test would be 0.09 lb/hr (43 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 0.014 lb/hr-ft² (74 g/hr-m²). On a coal-firing-rate basis, the CAH ash deposition rate would be 0.040 lb/MMBtu (18.5 g/10⁶ kJ). These calculated values are nearly identical to the Illinois No. 6 test results in December 1997. A comparison with the February 1998 test period is not possible since EERC personnel attempted to clean the CAH tube bank during the February test period.

A discussion of coal ash, slag, CAH ash deposit, and baghouse ash composition is not possible at this time because sample analyses are incomplete. A summary of these data will be presented in a subsequent quarterly technical progress report.

Testing of the LRAH Panel

Initial shakedown and testing of the LRAH panel occurred in December 1997. Testing of the LRAH panel continued this past quarter, evaluating LRAH panel performance relative to heat transfer, tile and tube temperatures, and cooling air temperatures and flow rates while an Illinois No. 6 bituminous coal was fired. Generally, the performance of the LRAH panel this past quarter was as anticipated, with no significant process problems. However, after 116 hr of coal firing, two ceramic tiles failed, forcing early termination of the August test period.

One of the objectives of the August test was to produce 2000°F (1094°C) air from the LRAH panel. This was achieved on August 18 and is believed to be a record high temperature for clean air produced with a heat exchanger while firing coal. This temperature was reached by reducing the cooling air flow rate and increasing the main burner firing rate from 2.26 to 2.38 MMBtu/hr (2.35 to 2.48 x 10⁶ kJ/hr) by increasing the coal feed from 200 to 210 lb/hr (90 to 95 kg/hr). The 2000°F (1094°C) cooling air exit temperature was achieved at a cooling air flow rate and pressure of 100 scfm and 100 psig (2.8 m³/min and 7 bar), respectively. These conditions were only maintained for several minutes, enough time to log the data in the historians and print the SFS process screens. The corresponding LRAH tube surface temperature was 2225°F (1219°C). The optical pyrometers indicated a nominal furnace flame temperature of 2980°F (1638°C) and a flue gas temperature near the surface of the LRAH tiles of nominally 2830°F (1555°C).

Approximately 4 hr later, after the cooling air exit temperature was reduced to <1800°F (927°C), the test was terminated because of the breakup of two ceramic tiles. Inspection after the test indicated that the large lower tile failed and fell into the bottom of the furnace, causing the large middle tile to also fail and fall. The large upper tile apparently remained in place because of the slag bonding it to the wall. The loss of the tiles was evident immediately as a function of tube surface temperature and cooling air temperature alarms. Coal feed was discontinued, and natural gas firing was initiated at a low rate, 1.2 MMBtu/hr (1.3 x 10⁶ kJ/hr), to control furnace cooldown. The maximum recorded tube surface temperature as a result of the tile loss was 2563°F (1406°C), with a corresponding cooling air exit temperature of 2137°F (1170°C). It is possible that the actual maximum temperatures were somewhat higher, because the data acquisition system records data only every 3 minutes for the LRAH panel.

Exhibit 2.2-22 is a photograph of the furnace interior after the August test period. The photograph displays the LRAH without the two LRAH panel tiles, damage to tiles on the right edge of the SRAH panel, and refractory damage above the SRAH panel. Exhibit 2.2-23 illustrates the status of the tile/brick (LRAH panel) cracking after the August test. The two missing tiles are indicated and the remaining LRAH tiles have a fairly uniform layer of slag/refractory on the surface. This material is strongly attached and cannot be removed. All of the seams between the remaining tiles/bricks are filled with slag, but the slag is cracked in all of the seams except the seam between the small upper tile and large upper tile. There are six visible cracks in the top support brick. The small upper tile (replaced in April prior to the lignite tests) has two vertical cracks and one horizontal crack. The horizontal crack extends completely across the face of the tile.

Exhibit 2.2-22
Photograph of LRAH and SRAH Panels Inside of the Slagging Furnace Following the August Test Period

LRAH Panel Condition
After Run SFS-RH5-0598
8/28/98

Exhibit 2.2-23
Illustration of Cracks Found in the Ceramic Tiles/Bricks of the LRAH Panel after Testing in August 1998

The large upper tile (replaced in April prior to the lignite tests) has a vertical crack on the right edge, and the lower right corner has been broken, leaving a gap of 0.125 to 0.25 in. (0.32 to 0.64 cm). These cracks were observed following the June test period and do not appear to have gotten any worse. The cracks on the left edge of the large upper tile formed as a result of the August test period. As earlier indicated, the large middle and lower tiles are missing pieces of these tiles were found lying in the bottom of the furnace.

Two vertical cracks are evident through the face of the small lower tile. These cracks have been present since the LRAH panel was initially tested while natural gas was fired in December 1997. The small lower tile is severely eroded/corroded as a result of slag flow over the surface. The wastage is much greater than with the other bricks, possibly because this brick protruded more into the furnace than the other bricks, creating an edge at the top that could be corroded on two surfaces (top and side) simultaneously. Other cracks previously visible in the surface of this tile are no longer visible because of slag coverage. The small bottom support brick has three vertical cracks through its face. Two of these cracks are new since the March test period.

Inspection of the two tiles that fell to the bottom of the furnace showed cracks from all four edges radiating to the center of the large lower tile. This may explain the tile loss. However, a missing piece on the lower edge of the tile may have been responsible. The mass of refractory found on the surface of the tile is believed to be the result of the tile pieces lying in the bottom of the furnace subsequent to breakup. The large middle tile did not break up substantially when it fell into the bottom of the furnace.

Based on inspections by EERC and UTRC personnel, all of the LRAH panel tiles and support bricks will require replacement before any future test period can be scheduled. The anticipated schedule for replacing the LRAH panel tiles/bricks is late November. The EERC will continue to document ceramic tile/brick cracking after each test is completed with the LRAH panel.

Inspection of the LRAH tubes indicates that they survived the temperature excursion as a result of the tile loss with no obvious damage. The tubes do not appear to have warped. Also, no ash/slag appears to be imbedded in the surface of the tubes. Exhibit 2.2-24 illustrates the condition of the LRAH tubes. A light ash dusting appears on the surface of the tubes that were not directly exposed to the furnace flame. The metal surfaces exposed directly to the furnace flame have an ash coating that is somewhat sintered, but no serious damage is evident. The inlet and outlet cooling air headers of the LRAH panel were unbolted to permit replacement of gaskets that had begun to leak as a function of repeated heating and cooling cycles. The gaskets in the outlet header were found to be in very poor condition. Also, one threaded thermocouple fitting on the cooling air outlet header will be replaced because it has developed a leak.

Exhibit 2.2-24
Photographs of the LRAH Tubes from Inside the Furnace

To date, the LRAH panel has been exposed to a range of furnace-firing conditions for a total of 1005 hr. Natural gas firing represents 620 hr and coal-lignite firing represents 385 hr. In addition, the LRAH panel has been exposed to eight heating and cooling cycles. The longest continuous coal-fired period was 80 hr, completed in March 1998. The EERC had planned to fire coal for 200 hr in August, but as mentioned before the LRAH tile breakup caused termination of the test at 116 hr..

Exhibits 2.2-25 through 2.2-27 summarize the LRAH ceramic tile temperatures, tube surface temperatures, and cooling air temperatures for the August test period. The cooling air flow rate data for the LRAH panel were summarized in Exhibit 2.2-17. Exhibit 2.2-28 illustrates the location of thermocouples in the LRAH panel, and Exhibit 2.2-29 provides a description of the LRAH thermocouples.

Exhibit 2.2-25
LRAH Ceramic Tile Temperatures Versus Run Time

Exhibit 2.2-26
LRAH Tube Surface Temperatures Versus Run Time for the August Test Period

Exhibit 2.2-27
LRAH Cooling Air Temperatures Versus Run Time for the August Test Period

Exhibit 2.2-28
Thermocouple Locations in the LRAH Panel

The indicated ceramic tile surface temperatures ranged from nominally 1766° (964°) to 2315°F (1269°C) once the SFS had stabilized thermally (Run Hours 52 through 143 and 152 through 197). Indicated tile temperatures increased during the high-temperature (2000°F/1094°C) air test to values ranging from 2063° to 2452°F (1129° to 1345°C). The highest tile surface temperature, 2487°F (1364°C), was measured at the lower left corner of the large middle tile during the high-temperature air test. However, based on an inspection of the inside of the LRAH panel with a boroscope before the April 1998 test period, the thermocouples (T19, T22, and T25) measuring surface temperatures at the center of each of the three large ceramic tiles were found to be no longer attached. Therefore, although the data from these thermocouples are presented in the Exhibit, they are believed to be invalid.

Exhibit 2.2-29
Description of LRAH 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	Top 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	Middle of middle tube facing cold side
	12	RAHT7	Middle of middle tube facing other tube
	13	RAHT8	Middle of the middle tube (failed, ND2) facing toward furnace
	14	RAHT10	Between 5 and 8 facing toward furnace
	15	RAHT13	Top of left tube facing cold side
	16	RAHT14	Top of left tube facing toward furnace
	17	RAHT15	Bottom of left tube facing cold side
	18	RAHT16	Bottom of left tube facing toward furnace
	19	RAHT17	Bottom of left tube facing toward side wall
	20	RAHT28	Top of right tube facing toward furnace
	21	RAHT29	Bottom of right tube facing toward furnace
Inner Surface of Monofrax bricks	22	RAHT19	Top brick, center
	23	RAHT20	Middle brick, right top corner
	24	RAHT21	Middle brick, left top corner
	25	RAHT22	Middle brick, center
	26	RAHT23	Middle brick (failed, ND2, hr 97), right bottom corner
	27	RAHT24	Middle brick (failed, ND2, hr 97), left bottom corner
	28	RAHT27	Middle brick (failed, ND2, hr 97), bottom center edge
	29	RAHT25	Lower brick, center
	30	RAHT26	Lower brick (failed, ND2, hr 97), top of center edge

¹ Thermocouple locations are illustrated in Exhibit 2.2-28.

With the exception of the high-temperature air test, the highest tile surface temperatures were typically measured at the top corners of the large middle tile where the ceramic material is thinner and the potential for flue gas leak effects is greatest. Tile surface temperatures during the August test period were higher than the temperatures observed during the lignite-fired tests probably because of the greater flame intensity when the bituminous coal was fired. The temperatures are

more similar to those for the February Illinois No. 6 test, although the locations of some of the thermocouples may differ, so a direct comparison is not appropriate.

LRAH cooling air flow rates during the August test period were controlled at 100, 150, 180, and 200 scfm (2.8, 4.2, 5.1, and 5.7 m³/min) with most test periods making use of either 180 or 200 scfm (5.1 or 5.7 m³/min). Changes in cooling air flow rates had a definite effect on indicated tile surface temperatures. As cooling air flow rates were reduced, tile surface temperature increased. Subsequently, when cooling air flow rates were increased, tile surface temperatures decreased. This effect is visible in the Exhibit with each change in cooling air flow rate.

LRAH tube surface temperatures ranged from nominally 1412° to 2019°F (767° to 1104°C). The low end of the temperature range represents the back side of the tube surfaces near the cooling air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the cooling air outlet. Changes in cooling 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 cooling air exit and on the front side of the tubes.

Again, the tube surface temperatures were higher when the bituminous coal was fired in August compared to the lignite-fired test periods. The tube surface temperatures observed in August are also slightly higher than those observed in February the same fuel was fired. The most likely reason for this difference is the higher firing rate in August because of the presence of the SRAH panel.

Cooling air temperature data are presented in Exhibit 2.2-27. The cooling air inlet temperature was fairly stable, nominally 1190° to 1230°F (644° to 666°C). During one test period, the cooling air inlet temperature was as low as 1180°F (638°C), and during the high-temperature air test, the cooling air inlet temperature was as high as 1250°F (677°C). Outlet cooling air temperatures ranged from nominally 1620° to 1780°F (882° to 971°C). The effect of cooling air flow rate can be seen in the cooling air outlet temperature data. As cooling air flow rate decreases, cooling air exit temperature increases, as expected. These cooling air flow rate changes are noted at Run Hours 96, 103, 153, 190, and 200 (flow rate reductions) and 108, 115, 185, and 203 (flow rate increases).

Heat recovery data from the LRAH panel are presented in Exhibit 2.2-30 for the August test period. At cooling air flow rates of 100, 150, 180, and 200 scfm (2.8, 4.2, 5.1, and 5.7 m³/min), the heat recovered from the LRAH panel during coal firing was:

93,550 Btu/hr (98,695 kJ/hr),
97,580 to 101,290 Btu/hr (102,947 to 106,861 kJ/hr),
102,580 to 119,355 Btu/hr (108,222 to 125,920 kJ/hr), and
107,100 to 129,030 Btu/hr (112,990 to 136,127 kJ/hr), respectively.

Exhibit 2.2-30
LRAH Heat Recovery Versus Tun Time for the August Test Period

For cooling air flow rates of 180 and 200 scfm (5.1 and 5.7 m³/min), the heat recovery ranges are a function of main burner swirl adjustment (0%, 25%, and 50%). The main burner firing rate was nominally 2.2 to 2.3 MMBtu/hr (2.3 to 2.4 x 10⁶ kJ/hr). One test period was performed at a slightly lower firing rate, 2.06 MMBtu/hr (2.16 x 10⁶ kJ/hr), and the high-temperature air test required a main burner firing rate of 2.4 MMBtu/hr (2.5 x 10⁶ kJ/hr). The firing rate distribution between the main and auxiliary burners was 75% main and 25% auxiliary. EERC personnel had planned to adjust the firing rate distribution between the main and auxiliary near the end of the 200-hr coal-fired test, but did not have the opportunity because of the LRAH tile loss.

A comparison of the LRAH panel heat recovery data for the August bituminous coal-fired tests and the previous lignite-fired test periods indicates that overall heat recovery was significantly greater, nominally 30%, when the bituminous coal was fired, even at a lower main burner firing rate. The higher fuel moisture content and lower peak flame temperature are the most likely reason for the lignite-fired tests to have resulted in lower LRAH heat recovery. A similar comparison with the February bituminous coal test periods also indicates that LRAH heat recovery was greater in August by nominally 23% to 36%. Since the main burner firing rates were similar, one possible explanation is the higher total furnace firing rate because of the presence of the SRAH panel. Another possible explanation is an overall change in heat losses and transfer in the furnace as a result of refractory-slag interactions. Some additional testing and further review of the data will be necessary to determine the cause of the apparent difference in LRAH heat recovery for the two bituminous coal test periods.

Testing of the SRAH Panel

Installation and initial testing of the SRAH panel occurred in April 1998. Testing of the SRAH panel this past quarter evaluated panel performance relative to heat transfer, tile temperatures, and cooling water temperatures and flow rates while Illinois No. 6 bituminous coal was fired. In general, the performance of the SRAH panel this past quarter was as anticipated, except for the failure of one of the water-cooled tubes and the loss of a piece of ceramic tile into the bottom of the furnace.

At about Run Hour 143 one of the water-cooled tubes in the SRAH panel failed, resulting in a water leak into the SRAH cavity. Coal firing was discontinued and natural gas firing was initiated in the main burner to assess the SRAH panel. Through furnace sight ports, the SRAH tiles looked black relative to the furnace refractory and the LRAH tiles, and a stream of water could be seen running out the bottom of the SRAH cavity. In order to stop the water leak, it was necessary to turn off the water to the proper tube. This was accomplished by turning the water flow off to each individual tube for a short period of time and verifying when the stream of water stopped running from the bottom of the SRAH cavity. Cooling water flow was restored to undamaged tubes without difficulty because the water leak had dramatically cooled the SRAH cavity. EERC personnel believe that the tube leak was the result of an imbalance in cooling water flow to the tubes, resulting in a steam condition in the failed tube and that the failed tube was in contact with or near the hot center support rail. Two other tubes in the immediate vicinity of the failed tube and support rail also showed signs of warping because of overheating.

Inspection of the SRAH panel after the August test revealed the presence of cracks in all of the SRAH ceramic tiles. The photograph in Exhibit 2.2-31 shows the condition of the SRAH tiles following the August test period. The photograph was taken from inside the furnace. The upper right tile appeared to have sustained the worst damage. The horizontal and vertical cracks across the face are evident as well as the hole along the right edge where a piece of tile is missing. This piece of tile was recovered from the slag tap prior to initiating coal firing. Extensive cracking and slag corrosion/erosion was observed in the small lower tile with the most damage appearing on the right side. The SRAH panel has a fairly uniform layer of slag/refractory on the surface.

Exhibit 2.2-32 illustrates the status of the tile/brick (SRAH panel) cracking after the August test period was completed. This slag is strongly attached to the ceramic tiles/bricks and cannot be removed. All of the horizontal seams between the tiles or bricks were filled with slag, although the slag was cracked in all of the seams. One vertical crack is visible in the top support brick. The small upper tile has a vertical hair-line crack in the lower left corner, but generally appears to be in good condition. The upper left middle tile has a crack on the lower edge. Four horizontal cracks are visible in the upper right middle tile, two completely across the face and two that are <4 in. (<10 cm) in length originating from the right edge. At least one of these cracks appears to have contributed to the breakup of this tile. The lower left middle tile has one visible horizontal crack across the top left corner, while the lower right middle tile has a horizontal crack across the lower edge. Three vertical cracks are visible in the small lower tile, along with two horizontal cracks connecting vertical cracks on the right side and to the right edge. All three vertical cracks effectively extend across the entire face of the small lower tile. There were three visible vertical cracks in the bottom support brick.

SRAH Panel
8/28/98
SRAH Condition
After Run SFS-RH5-0598

EEFC GW15685 CDR

Exhibit 2.2-31
Illustration of Cracks Found in the Ceramic Tiles/Bricks of the SRAH Panel after Testing in August 1998

Exhibit 2.2-32
Photographs of the SRAH Ceramic Tiles after the August Test Period

High-density refractory deterioration was also observed in an area immediately above the right side of the SRAH. The refractory deterioration is believed to have been caused by a combination

of refractory spalling and flame impingement. The flame impingement occurs when the main burner swirl setting is 50% or greater. The refractory hole permitted some slag to flow back into the SRAH panel cavity onto ceramic surfaces.

It has been determined that all of the ceramic tiles and most of the support bricks would require replacement before any future test period could be scheduled using the SRAH panel. Based on the condition of the SRAH panel, the cost to rebuild it, and plans for future use, UTRC has elected not to rebuild the SRAH panel. The primary objective for future use of the SRAH panel would have simply been for materials testing. UTRC and EERC personnel agree that future materials testing can be accomplished using the LRAH panel. Therefore, when the high-density furnace refractory is repoured, the opening for the SRAH panel in the furnace wall will be filled with appropriate layers of insulating, intermediate, and high-density refractory.

To date, the SRAH panel has been exposed to a range of furnace-firing conditions for a total of 562 hr. Natural gas firing represents 344 hr, and coal/lignite firing represents 218 hr. The longest continuous coal-fired period was 61 hr completed in August. In addition, the SRAH panel has been exposed to three heatup and cooldown cycles.

Exhibit 2.2-33 summarizes the SRAH ceramic tile temperatures for the August test period. Exhibit 2.2-34 illustrates the location of thermocouples in the SRAH panel, and Exhibit 2.2-35 provides a description of the SRAH thermocouples. The ceramic tile surface temperatures ranged from nominally 1640° (894°) to 2610°F (1432°C) once the SFS had stabilized thermally (Run Hours 65 through 143 and 159 through 206). The highest tile surface temperatures were generally measured at or near the furnace side of the tiles. Lower tile temperatures were measured on the back or cavity surface of the tiles or in the cavity.

Exhibit 2.2-33
SRAH Ceramic Tile Temperatures Versus Run Time for the August Test Period

Exhibit 2.2-34
Thermocouple Locations in the SRAH Panel

Exhibit 2.2-35
Description of SRAH Panel Thermocouple Locations ¹

Category	No.	Label	Description
Furnace	1	SRAH1	At interface between top and middle tile (not in place for ND2/RH5)
	2	SRAH8	At interface between third and bottom tile
Surface, furnace side	3	SRAH2	Middle tile, upper left (not in place for ND2/RH5)
	4	SRAH3	Middle tile, upper right
Surface, cavity side	5	SRAH4	Middle tile, upper left
	6	SRAH5	Middle tile, upper right (not in place for ND2/RH5)
	7	SRAH6	Middle tile, lower left
Cavity	8	SRAH7	Middle tile, lower right
	9	SRAH9	Middle tile, lower left
	10	SRAH10	Middle tile, lower right
Frame	11	SRAH11	Cooling air exiting frame

¹ Thermocouple locations are illustrated in Exhibit 2.2-34.

SRAH panel cooling was accomplished with water rather than air. Therefore, the ceramic tile temperature variability shown in Exhibit 2.2-33 is a direct result of furnace firing rate and main burner swirl setting. Cooling water flow rates are adjusted to control water exit temperature at <140°F (60°C). The total cooling water flow rate during the August test period was nominally 7 to 8 gal/min (26 to 30 L/min).

Heat recovery data from the SRAH panel are presented in Exhibit 2.2-36 for the August test. These data are calculated values based on the cooling water flow rate and measured differential temperature. The SRAH heat recovery was stable during stable furnace operating periods and fluctuated with changes in furnace firing rate, main burner swirl setting, and cooling water flow rate. Nominal values ranged from 108,970 to 133,330 Btu/hr (114,963 to 140,663 kJ/hr). However, values reported after the cooling water tube failure cannot be used for comparison with other SRAH data because of the effective change in surface area.

Exhibit 2.2-36
SRAH Heat Recovery Versus Run Time for the August Test Period

A comparison of the SRAH panel heat recovery data for the August bituminous coal-fired tests and the previous lignite-fired test periods indicates that overall heat recovery was greater by 12% to 20% when the bituminous coal was fired, even at a lower main burner firing rate. The higher fuel moisture content and lower peak flame temperature are the most likely reasons for the lignite-fired tests to have resulted in lower SRAH heat recovery. A comparison with the February bituminous coal test periods is not possible because the SRAH panel was not installed until this past April. Since additional testing with the SRAH panel is not anticipated, further review of the SRAH data is not warranted at this time.

Materials

Refractory Materials for the Radiant Air Heaters

During this reporting period, the performance of the RAH refractories was reviewed along with the furnace history and data that were provided by UNDEERC personnel. The refractories in the Large RAH panel were exposed to a range of furnace firing-conditions for a total of 1005 hours (620 hrs. on natural gas and 385 hrs. on coal/lignite fuel). The Small RAH panel had been exposed to a range of furnace-firing conditions for a total of 562 hours (344 hrs. with natural gas and 218 hrs. with coal and lignite).

The refractory tiles for the RAH were designed to be both a furnace lining and a heat transfer panel in the radiant air heater. As a result, the tiles had to be relatively thin. This is counter to conventional refractory practice in furnace linings, which are typically much thicker for structural

robustness and for holding the heat in. Two types of high alumina fusion-cast materials were used for the tiles: Monofrax M (α/β alumina) and Monofrax L (alumina spinel), which were selected because of their refractoriness and relatively high thermal conductivity.

Overall, these materials held up quite well in the RAH furnace during numerous thermal cycles and tests, as well as during some unscheduled sudden large temperature fluctuations. While cracks were present in many of the tiles, most of the tiles survived the entire campaign of the 7 LRAH runs. It appears that the slag penetrated the cracks and sealed them, so that they were not a threat to tile life. After the 7th furnace run, which included a high temperature test exposure (tile hot surface approaching 2800°F [1538°C]), the bottom and middle radiation tiles fell out of the LRAH panel during cooling. An examination of the panel indicated that the tiles may have fallen out as a result of the ledge on the bottom panel coming loose.

While there was some reaction of the tiles to the hot flowing slags during the normal RAH furnace runs, the extent of the tile erosion was small. Samples of the Monofrax M and L from the RAH furnace runs were cut up and analyzed for microstructural changes. The characterization of the slag reactions with the Monofrax L is discussed in this report. The reactions with the Monofrax M tile were discussed in the previous Quarterly Report. The results of laboratory slag tests on the two tile materials are also presented in this report. Notable differences were observed between the reactions of the two materials with the Illinois No. 6 coal slag. The corrosion effects in the laboratory slag test were more severe, but the types of reactions were consistent with the results observed in the tiles exposed in the RAH furnace.

Review of Refractory Performance in the UNDEERC Furnace Test Facility

There have been 7 furnace test runs for a total of 1005 hours with the fusion cast refractory tiles in the LRAH, and 3 furnace test runs for a total of 562 hours in the SRAH. The testing conditions are summarized in Exhibit 2.2-37. A combination of natural gas and various types of bituminous coal and lignite were used as the fuels. The furnace temperatures were operated above the fusion point of the coal slags, so that they would flow down over the tiles and collect on a slag screen below. The composition of the slags varied widely with the type of coal used, and reacted differently to the two different tile materials: Monofrax M, an α/β alumina refractory (94.5% Al_2O_3 with about 4% Na_2O) and Monofrax L, a magnesia/alumina spinel refractory (45% MgO , 54% Al_2O_3).

Exhibit 2.2-37
Furnace Run Summary – Furnace Test Facility at UNDEERC

Date	Fuel	LRAH*			SRAH*			Comments
		Run No.	Coal (hr)	Gas (hr)	Run No.	Coal (hr)	Gas (hr)	
30 Nov – 4 Dec '97	Natural gas	1	---	104	---	---	---	Natural gas only
14 – 19 Dec '97	Illinois No. 6 coal	2	35	80	---	---	---	Sudden temperature drop (power failure)
9 – 13 Feb '98	Illinois No. 6 coal	3	51	60	---	---	---	
16 – 20 Mar '98	Rochelle subbituminous	4	81	32	---	---	---	LRAH – replace top block and tile, and radiation tile
20 – 24 Apr '98	Falkirk lignite	5	50	120	1	50	120	
8 – 12 Jun '98	Center & Falkirk lignite	6	52	61	2	52	61	SRAH – replace top tile and top right radiation tile
7 – 19 Aug '98	Illinois No. 6 coal	7	116	163	3	116	163	Very high temp. test LRAH – center & bottom radiation tiles fell out
<i>Total</i>			385	620		218	344	
<i>Total coal & gas</i>			1005			562		

* *L = Large, S = Small; RAH = Radiant Air Heater*

The location of the tiles and support blocks in the LRAH and SRAH are shown in Exhibit 2.2-38. Monofrax M was used exclusively in the LRAH because of its high thermal conductivity and refractoriness, and the three center radiation tiles (marked B in Exhibit 2.2-38) were coated with a chromium oxide layer in order to increase the emissivity on the back face adjacent to the heat exchanger tubes. Both Monofrax M and L tiles were used in the SRAH, and their location is also shown in Exhibit 2.2-38. The top left Monofrax M tile had a chromium oxide coating on the front (hot) face in order to enhance the resistance to slag corrosion. The support top blocks and side rails (not shown) were made of Aurex 30 (30 Cr₂O₃ and Al₂O₃).

Exhibit 2.2-38
Location of Large and Small RAH Refractory Tiles

It should be emphasized that the tiles for this application were specifically designed to be effective radiation panels, where high thermal conductivity, mechanical and chemical stability over a wide temperature range were important parameters. These materials were commercially available. There were other chromium containing compositions, which would be more resistant to slag corrosion, but their thermal conductivities were too low for acceptable heat transfer levels.

The thin sections of the tiles were of concern, since in normal refractory practice, the section thickness of shapes is much greater, so that they can support heavier loads during processing and service. In the RAH design, the tiles with tongue and groove ends (Exhibit 2.2-39) are supported by side rails, so that the vertical loads on the tiles can be much lower. However, the structural integrity and robustness of the tiles are reduced due to their large aspect ratios (length to thickness ratio), and hence a concern for possible failure during sudden thermal and mechanical shock. This was not the case, however, and the following discussion briefly summarizes the performance of these refractories during the furnace tests.

note: the cross-hatched lines were for dimensional measurements

Exhibit 2.2-39 Dimensions of the Center Radiation Tile (LRAH)

LRAH Tile Performance

LRAH Run No. 1

The heat-up rate for the first furnace run with the newly installed refractories was limited to 150°F/hr (83°C/hr) while firing natural gas at a reduced (75%) load. The objective of this run was to verify the anticipated operating RAH parameters. Thermocouples were mounted in the back of the LRAH tiles, and their location is shown in Exhibit 2.2-40. The highest temperature recorded was about 1850°F (1010°C) for TC-21, which is located at the top left, back side of the top radiation panel. The recorded temperatures in subsequent furnace runs were usually the highest at this location, where the tile is also the thinnest (about 1" [25mm] thick). The temperature of the center of the three large tiles ranged from 1610°F to 1650°F (877° to 899°C), which indicates that there are significant thermal gradients across the back (radiation) surface. The peak temperature (Exhibit 2.2-41) was held for about 35 hours out of a total run time of 104 hours.

Inspection of the tiles and supporting refractories by UNDEERC personnel after the run showed that all of the blocks and tiles remained intact. However, all 5 of the fused-cast Monofrax M tiles had some visible cracks. Most of these cracks were probably in the tiles before they had been machined, but many were too small to be seen at the time. The fusion cast products often have small cracks that occur during cooling, but these have not prevented their use or limited their service life as glass tank refractories. As will be discussed later, the fluid slag penetrates these

cracks and serves as a beneficial crack filler and cement. The bottom Aurex 30 block also had one vertical crack.

Exhibit 2.2-40
Location of Thermocouples on Back (Cool) Face of Radiant Heat Tiles
(Labeled B in Exhibit 2.2-38) in the LRAH

Exhibit 2.2-41
Back Face LRAH Ceramic Tile Temperatures vs. Run Time for the First Furnace Run
Fired with Natural Gas at 75% Load (LRAH Run No. 1)

LRAH Run No. 2.

During the second test run, the furnace was fired on natural gas at 100% load and later with Illinois No. 6 bituminous coal at 100% load. The purpose of this test was to complete the initial testing of the LRAH panel. The temperatures in the tile refractories are shown in Exhibit 2.2-42. The tile temperatures ranged from 1940°F to 2355°F (1060°C to 1291°C) when firing the furnace system on natural gas at 100% load. Thermocouples measuring the rear face surface temperatures at the center of the radiation tiles (Exhibit 2.2-38, location B) indicated nominal temperatures of 1940°F to 2064°F (1060°C to 1129°C). A problem arose when a power outage occurred during the gas firing at about 35 hours into the run. This caused the tile back face temperatures to drop by 400°F to 500°F (220°C to 280°C), within an hour (see Exhibit 2.2-42). This would expose the tiles to thermal shock conditions. However, the tiles withstood the sudden temperature change, and the cracks in the tiles after firing in natural gas at the 75% and 100% loads are shown in Exhibit 2.2-43. All of the cracks in the tiles that were identified in the Exhibit were evident after the 75% load test firing natural gas. Some of the longer cracks showed evidence of linear growth following the 100% load test. In the small lower tile, two cracks extended completely across the surface after the 75% gas load firing.

When the coal firing (Ill. No. 6 coal) was stabilized during the second part of the run (Exhibit 2.2-42), the back face tile temperatures ranged from 1960°F to 2370°F (1071°C to 2370°C). The temperature at the back face of the three large radiation panels varied between 1960°F to 2071°F (1071°C to 1133°C). However, these temperatures are probably low since the thermocouples had pulled free from their cemented positions at the back face of the tile.

Exhibit 2.2-42
Back Face LRAH Ceramic Tile Temperatures vs. Run Time for Natural Gas- and Coal-Fired Tests at 100% Load (LRAH Run No. 2)

Exhibit 2.2-43.
Location of Cracks in the Monofrax M Tiles of the LRAH Panel after the First Furnace Run with Natural Gas at 75%, and Later at 100% Load

Exhibit 2.2-44 shows photographs of the LRAH panel following the coal-fired test. The left photo shows that the coal slag has flowed over and completely covered the top block (Aurex 30, a chrome-alumina brick) and a portion of the small upper tile. Similarly, the right photo shows a portion of the top radiation tile and middle radiation tile that are also covered with a thin layer of the slag, which was fully melted (fluid) at 2520°F (1382°C). The gaps between the tiles and block occurred as a result of shrinkage during the cooling of the furnace. The photographs show evidence that slag had dripped from the upper block edge to the lower tile, and that some of this dripping occurred as the brick and tiles were cooling (shrinking). The slag between the edges of the block and tile is cracked, which apparently occurred during cooling, and did not appear to have frozen the tile in place. Since the slag covered the tile, many of the cracks were covered and were difficult to see.

(A)

(B)

Exhibit 2.2-44
LRAH Top Ceramic Block and Tile (A), and Large Middle Tiles (B) after the Coal-Fired Test at 100% Load (Run No. 2)

LRAH Run No. 3.

The furnace heat-up rate was limited to 150°F/hr (83°C/hr) under natural gas firing. When the furnace temperature reached 2800°F (1538°C), which was the original design operating temperature, it was held for 10 - 18 hours to permit the furnace refractories to come to thermal equilibrium. The furnace was then fired with natural gas and Illinois No. 6 bituminous coal at 100% load. The back face temperatures reached as high as 2350° (1288°C, TC 21, Exhibit 2.2-40). Examination of the refractories after this run by UNDEERC employees indicated that the ceramic tiles were entirely coated with a slag layer, and that there was a crack across the face of the small upper tile as well as evidence of some slag erosion/corrosion occurring on the tile surface.

LRAH Run No. 4.

The furnace heat-up rate using natural gas was the same as in furnace Run No.3, and as soon as the furnace temperature reached 2700°F (1482°C), coal firing (Rochelle subbituminous coal) was initiated and continued for 80 hours at nominally 2800°F (1538°C). The back face

temperatures reached as high as 2345°F (1285°C, TC 21). During this run, a coal feed plug resulted in a slight pressure surge and may have caused some mechanical shock to the refractories. Exhibit 2.2-45A shows the status of the tile and block cracking after this test. All of the 6 Monofrax M tiles and top and bottom support blocks (Aurex 30) had one or more visible cracks on the surface. The changes in the crack growth and number can be seen when compared with those in Exhibit 2.2-43. On the bottom support block, the large lower tile, and the small upper and lower tiles, these cracks extended completely across the surface. Also, the small upper tile had a piece of ceramic broken out of the lower left corner.

(A)

Run No. 4, after natural gas and
Rochelle subbituminous coal
(March 1998)

(B)

Run No. 6, after natural gas and
Center & Falkirk lignite coal
(June 1998)

Exhibit 2.2-45

Location of Cracks in LRAH Tiles after LRAH Runs No. 4, No. 6, and No. 7 in the
UNDEERC Pilot Test Facility

(C)

Run No. 7, after Natural Gas and Illinois No. 6 Bituminous Coal (Aug 1998)

Exhibit 2.2-45 (cont.)

Location of Cracks in LRAH Tiles after LRAH Runs No. 4, No. 6, and No. 7 in the UNDEERC Pilot Test Facility

It was therefore decided to replace the small upper Monofrax M tile before the next test. This tile was removed and sent to UTRC for examination and characterization.* In addition, UNDEERC and UTRC personnel elected to replace the large upper tile in order to examine and characterize a large tile that had been exposed to slags from bituminous and subbituminous coal, since the following tests would be using lignite. The small piece of ceramic tile that was stuck to the large middle tile was left in place (Exhibit 2.2-45A). Overall, even though the degree of cracking observed appeared to be extensive, there was no indication of any impending failure of the remaining tiles and bricks.

Exhibit 2.2-46A shows the replaced tile in the LRAH on the left side of the photo. On the right side of this photo is shown the installed SRAH panel, which was tested in the next furnace run.

* The results of the characterization study were reported in the previous Quarterly Report

(A)

(B)

Exhibit 2.2-46

(A) Replacement of Top Cross Panel and Radiation Panel in LRAH on Left Side, and Installation of SRAH Panels on Right Side after LRAH Run No. 4. The Dark Top Vertical left Panel in the SRAH has been Coated with Cr-Oxide. (B) Shows the Slag Coated RAH Panels after LRAH Run No. 5 using Natural Gas and Falkirk Lignite.

LRAH Run No. 5.

This was the first run where the SRAH was installed and where Falkirk lignite was used. The heat-up rate was limited to 50°F/hr (28°C/hr) during the natural gas firing in order to cure the new refractories. During the coal firing at 100% load (Coal-Creek Falkirk lignite) the furnace temperature was controlled between 2700°F and 2800°F (1483° to 1588°C). The maximum rear face tile temperature was 2260°F (1238°C), which is about 90°F (50°C) cooler than when being heated by the Illinois No. 6 coal. The lignite slag is more corrosive to high alumina refractories than the Illinois No. 6 coal slag. Exhibit 2.2-46B shows that the RAH tiles were coated to a significant degree with a layer of slag. The slag also contained dissolved alumina castable used in the furnace lining. Most of the slag/castable was tightly bonded to the tiles. The slag compositions are shown in Exhibit 2.2-47. The lignite slag has less silica and alumina than the Illinois No. 6 coal slag, but the calcia and magnesia are higher by 2.5x and 7x, respectively. The results of slag corrosion tests on the Monofrax M and L tiles will be discussed later.

Exhibit 2.2-47
Typical Composition of Major Constituents in Coal Slags

Composition	Illinois #6	Rochelle Subbituminous	Falkirk Lignite
SiO ₂	54	27	34
Al ₂ O ₃	19	16	12
Zr ₂ O ₃	16	6	7
P ₂ O ₅	0.1	0.8	0.3
CaO	7	23	18
MgO	1	7	7
Na ₂ O	1	2	3
SO ₃	3	16	18
<u>Ash Fusion Temp.</u>	<u>(°F)</u>	<u>(°F)</u>	<u>(°F)</u>
Initial	2340 ± 9	2250 ± 40	2180 ± 9
Fluid	2520 ± 15	2270 ± 50	2210 ± 9

LRAH Run No. 6.

This run also included lignite (Center and Falkirk lignite) in the firing tests. The heat-up rate was 150°F/hr (83°C/hr) on natural gas firing. The maximum back face temperature was 2270°F (1244°C) when the furnace was fired with the lignite at 100% load. The thermocouple temperatures as a function of run time are shown in Exhibit 2.2-48. Note that there were several significant temperature fluctuations caused by problems in the coal feed rate to the furnace, which is related to the high moisture content of the lignite. TC 21, which is located at the top left back face of the center radiation tile, continues to be the hottest measured location.

The LRAH panel was coated fairly uniformly with a layer of the slag, which was strongly attached and could not be removed. All of the seams between the tiles and bricks were filled with slag, but the slag was cracked in all of the seams except the seam between the small upper tile and large upper tile. Exhibit 2.2-45B shows the location of visible cracks in the LRAH after this run. There is one crack in the upper right corner of the top support block. Three vertical cracks previously seen across the face of this brick are no longer visible because of slag coverage. The small upper tile that was used as a replacement after Run No. 4, had a short vertical crack originating from the top edge, but generally appeared to be in good condition.

Exhibit 2.2-48
Back Face LRAH Ceramic Tile Temperatures versus Run Time for the June Test Period
(LRAH Run No. 6)

There were no plans to replace any of the LRAH tiles prior to the next run. After this test, the total furnace run time on the LRAH was 726 hours (457 hours on natural gas and 269 hours on coal/lignite).

LRAH Run No. 7

One of the objectives of this run was to produce 2000°F (1093°C) air from the LRAH panel, which was accomplished at the end of the run. This is believed to be a record for 2000°F clean air produced from a heat exchanger using coal as the fuel.

The initial furnace heat-up rate using natural gas was 50°F/hr (28°C/hr). When thermal equilibrium was reached at approximately 2800°F (1530°C), Illinois No. 6 bituminous was fired at 100% load continuously for a period of 61 hours. The maximum recorded tile temperature was about 2315°F (1269°C). A water leak occurred in the SRAH, so that the furnace had to be shut down for repairs, and the tile temperatures dropped by about 400°F (222°C), and took about 8 hours before the furnace temperature was back up to its operating level. The firing was continued for another 55 hours. During the last 8-10 hours, which was the high temperature test, the tile temperatures went as high as 2487°F (1364°C) at the back face of the lower left corner of the large middle (radiation) tile. At furnace run 200 hours, TC-21 indicated a peak (spike) temperature of 2725°F (1496°C). The temperature vs. time curves are shown in Exhibit 2.2-49.

Exhibit 2.2-49
Back Face LRAH Ceramic Tile Temperature vs. Furnace Run Time in August
(LRAH Run No. 7)

Four hours after the cool down from 2000°F (1093°C) to 1800°F (1000°C) of the exit air temperature, the large lower tile fell into the bottom of the furnace, causing the middle tile above it to fall also. Inspection by UNDEERC personnel of the LRAH panel revealed several cracks in the remaining tiles, which are shown in Exhibit 2.2-45C. The two missing tiles are indicated, and the remaining tiles have a fairly uniform layer of slag/castable on the surface. This material was strongly attached and could not be removed. All of the seams between the tiles and blocks were filled with the slag. This slag was cracked in all of the seams except for the seam between the small upper tile and the large upper tile. The small upper tile, which had been replaced after LRAH Run No. 4 prior to the lignite tests, had two vertical cracks and one horizontal crack. The horizontal crack extended completely across the face of the tile. The large upper tile (also replaced after Run No. 4) had a vertical crack on the right edge, and the lower right corner was broken, leaving a gap of 0.125 to 0.25 in. (3.2 to 6.4 mm). These cracks were observed following the previous furnace run and did not appear to be any worse.

The falling out of the lower two large tiles was probably due to several factors, since they had undergone eight heating and cooling cycles, had been exposed to several sudden changes in temperature, and had also been exposed to the corrosive action of the bituminous coal and lignites. The high temperature firing test may have been the final factor causing the tiles to fall away from their side supports. The very high tile temperatures, >2500°F (1371°C), probably fluidized or weakened the slags that penetrated (and cemented) the cracks, which had helped to hold the tiles together and which also bonded the tiles at the seams. Also, it appears that the ledge on the bottom support block came loose.

Overall, the LRAH panel had been exposed to a range of furnace-firing conditions for a total of 1005 hours (620 hrs. on natural gas and 385 hrs. on coal/lignite fuel). The overall dimensions of the tiles changed very little, although there was discoloration up to ¼" (6 mm) into the front surface of the Monofrax M tile due to penetration of some of the slag constituents.

All of the LRAH refractories (tiles and blocks) will be replaced before the next furnace test. Sections and full tiles were returned to UTRC for examination, characterization, and assessment of their performance. This information will be used also to guide the inputs for developing improved refractories for future furnace runs.

SRAH Tile Performance

One of the purposes of the SRAH panel was to test different refractory materials. Monofrax L tiles were used in this series of tests along with the Monofrax M tiles. Their location in the panel is shown in Exhibit 2.2-38. Note that all of the tiles are Monofrax L, except for the top left tile and bottom right tile, which are Monofrax M. The top left Monofrax M tile was coated with chromium oxide in order to provide greater protection for the corrosive/erosive action of the flowing slags.

SRAH LRAH Run No. 1 (LRAH Run No. 5)

The furnace firing conditions were described in the LRAH Run No. 5. In addition to the initial heating with natural gas, Falkirk lignite was the first coal-based fuel that the panels were exposed to. The maximum tile temperature measured was 2570° (1410°C). The thermocouple indicating this high temperature was located 1/8" (3 mm) behind the hot face of the tile. Following this test, the upper support block (Aurex 30), the small upper tile (Monofrax L), and the top right middle tile (Monofrax L) suffered sufficient cracking that they were replaced prior to the next test. The entire panel had a fairly uniform layer of slag/castable on the surface, except for a small area of scale type pieces that were removed from the Monofrax L tiles that were to be replaced. Exhibit 2.2-50 shows the slag-covered face of the small upper tile of Monofrax L that was removed from the SRAH and was returned to UTRC for examination and characterization.

Exhibit 2.2-50
Top Monofrax L Tile from SRAH after First Falkirk Lignite Firing (SRAH Run No. 1).

Exhibit 2.2-51
Cross-Section of Sample from Top Monofrax L Tile in Contact with Slag after First Falkirk Lignite Firing (SRAH Run No. 1)

A cross-section of this tile is shown in Exhibit 2.2-51 at two magnifications. The slag surface is at the top of the photo. The slag layer, and the adjacent reaction zone, which is about 150µm thick, can be seen. The open pores in this region have been filled with the Falkirk lignite slag. The area below is the unreacted Monofrax L, which contains the pores that were in the original tile. Several of these pores have been penetrated with the slag.

An electron microprobe back-scatter electron photograph of this reaction layer and a portion of the underlying Monofrax L material can be seen in Exhibit 2.2-52, along with element maps of Al, Si, O, Na, Ca, Fe and Mg. The oxides of Al and Mg are major constituents in both the slag and the Monofrax L. The Si, Na, Ca, and Fe are prevalent oxides only in the slag. The presence of Si, Fe, Ca oxides can clearly be seen within the reaction zone and indicate that the slag has reacted with the Monofrax L to alter its composition. The magnesium element map distinguishes this reaction zone (by its presence as a uniform blue color) from the unaltered Monofrax, where it appears as islands of higher concentration (color ranging from green to yellow) in a uniform blue background. Monofrax L is made up of pure MgO in a matrix of spinel ($\text{MgO} \cdot \text{Al}_2\text{O}_3$); the MgO stands out in the element map as yellow/green islands in the spinel microstructure.

Exhibit 2.2-53 shows a comparable photograph and element maps of a region away from, but still near, the slag surface. Comparison of the element maps in the two Exhibits clearly shows that the dark spots (absence of Al) in the aluminum map in Exhibit 2.2-53 contain Mg-rich islands (MgO), and that the material in Exhibit 2.2-53 is unaltered Monofrax L. However, small amounts of Ca, Fe, and Si from the slag have penetrated the pores and grain boundaries in the Monofrax L.

The electron microprobe element scans show that in regions away from the reaction zone, the Mg and Al peak heights are identical in the Monofrax L. In the reaction zone, the Al peak height

is twice that of the Mg peak. The MgO content in the slag (Exhibit 2.2-47) is much lower than that of Al_2O_3 .

B.S.E.

Aluminum

Silicon

Oxygen

|—|
33 mm

Exhibit 2.2-52
Electron Microprobe Maps of Region Adjacent to Slag Contact Surface of Monofrax L
Sample Shown in Exhibit 2.2-51

Sodium

Calcium

Iron

Magnesium

|—|
33 mm

Exhibit 2.2-52 (cont.)
Electron Microprobe Maps of Region Adjacent to Slag Contact Surface of Monofrax L
Sample Shown in Exhibit 2.2-51

B.S.E.

Aluminum

Silicon

Oxygen

|—|
33 mm

Exhibit 2.2-53
Electron Microprobe Maps of Region Near Slag Surface of Monofrax L Sample Shown in Exhibit 2.2-51

Sodium

Calcium

Iron

Magnesium

|

Exhibit 2.2-53 (cont.)
Electron Microprobe Maps of Region Near Slag Surface of Monofrax L Sample Shown in Exhibit 2.2-51

Examination of the thickness of the upper Monofrax L tile indicated that the Falkirk slag did not erode the tile to any measurable degree. The results from optical and electron microprobe analyses indicated that the slag penetrated and reacted with the Monofrax L up to a depth of approximately 150 μm , and that this altered zone remained attached to the parent material.

SRAH LRAH Run No. 2.

The furnace firing conditions were described in the LRAH Run No. 6 section. Center and Falkirk lignites were used in addition to natural gas. The highest recorded tile temperature was 2570°F (1410°C) after the furnace had stabilized thermally. This high furnace temperature was recorded near the hot face (furnace side) of the tile. The SRAH panel was nearly covered with a uniform, adherent layer of slag. All of the blocks and tiles appeared to be intact after the run. Exhibit 2.2-54A shows the location of the visible cracks in the panel after this run. The upper right middle tile of Monofrax L, which was replaced after the previous run, had a horizontal crack across the surface. The lower left middle tile had no cracks, and the lower right middle tile had a horizontal crack across the lower edge. The lower tile had two vertical cracks, one of which ran across the entire face. None of the cracks appeared to be serious, so that the panel was used in the next furnace run.

(A)

SRAH Run No. 2. After natural gas and Center & Falkirk lignite.

(B)

SRAH Run No. 3. After natural gas and Illinois No. 6 bituminous coal.

Exhibit 2.2-54

Location of Cracks in SRAH Tiles after SRAH Furnace Runs No. 2 and No. 3 in the UNDEERC Test Facility

SRAH LRAH Run No. 3.

The furnace firing conditions were described in the LRAH Run No. 7 section, which is the run with the highest temperature. The highest recorded tile temperature was 2610°F (1432°C). At about Run Hour 143, one of the water-cooled tubes in the SRAH panel failed, resulting in a water leak into the SRAH cavity. Coal firing was discontinued and natural gas firing was initiated. The SRAH tiles appeared to be black (cool) relative to the tiles in the LRAH (temperatures dropped by approximately 600° to 800°F [333° to 444°C]). Inspection by UNDEERC personnel of the SRAH panel revealed the presence of cracks in all of the tiles, which is shown in Exhibit 2.2-54B. By comparing Exhibit 2.2-54B with 54A, the extent of the cracks and crack growth becomes apparent. Notice that the upper right middle tile has many cracks and one lower right edge missing. Similarly, the small lower tile has several cracks running through the face. These cracks grew significantly and intersected since the previous run (Fig 16A). It is likely that the sudden temperature drop during the water leak contributed to the extensive cracking. In addition, the high temperature of the furnace and Illinois No. 6 slag caused significant slag corrosion/erosion. The slag was strongly bonded to the tiles. At the end of this run, the SRAH panel had been exposed to a range of furnace-firing conditions for a total of 562 hours (344 hrs. with natural gas and 218 hrs. with coal and lignite).

It was decided that all of the tiles, and most of the support blocks (Aurex 30) would have to be replaced before the next run. Selected sections of these refractories and some full tiles were sent to UTRC for examination and microstructural characterization.

Laboratory Slag Testing of Monofrax M and L

Monofrax Inc. personnel prepared crucibles (with covers) of Monofrax M and L and filled them with powdered Illinois No. 6 coal slag. The slag was melted and held at 2650°F (1450°C) for 100 hours in air. Sections cut through the crucibles after the test are shown in Exhibit 2.2-55. The lower ¼ of the crucible contained the slag, and it can be seen that the slag dissolved the Monofrax L, leaving an apparently clean interface. The slag in the Monofrax M crucible penetrated (discolored) into the Monofrax M, but the original crucible surface is intact.

Exhibit 2.2-55

Sections cut through Monofrax L crucible (A) and Monofrax M crucible (B) after reactions with contained Illinois No. 6 slag for 100 hours at 2640 °F (1450 °C) in air

Exhibit 2.2-56A shows electron microprobe element maps over a 7.6 mm (7596 μm) scan of the slag, the slag/Monofrax L interface and the underlying Monofrax L. Potassium and iron are two elements in the slag that are not present in the Monofrax L. Magnesium is in both the slag and the refractory. The magnesium map in the slag is visible at a lower level than in the Monofrax L (white region). There is a relatively thin reaction zone (170-260 μm thick) that contains both the slag constituents and Monofrax L. This reaction zone is discrete, and there is no evidence of potassium or iron diffusing into the Monofrax L. The net result is that the Illinois No. 6 slag attacks the Monofrax L, but keeps the corrosion to a narrow zone between the slag and the refractory. The dark zone between the slag and slag reaction layer is a crack.

Exhibit 2.2-56B shows comparable element scans of the Monofrax M crucible. The slag presents a sharp interface with the original Monofrax M surface. However, the depth of penetration of the slag into the Monofrax M is much greater, being 2-3 mm (2000-3000 μm). The original surface of the Monofrax remained intact, although the next 2-3 mm were penetrated by the slag. This was discussed in the previous Quarterly Report, where the slag penetrated into existing fine cracks in the refractory without disrupting its basic composition and structure.

Tests performed on these two refractories at the UNDEERC dynamic slag test facility showed similar results. In this test facility, the fluid slag was dripped into a catch basin at the top of a 4" x 4" x 9" (102 x 102 x 229 mm) block and then was allowed to flow down a vertical channel in the block as shown in Exhibit 2.2-57. Both refractory materials were exposed to flowing Illinois No. 6 slag at 2732°F (1500°C) for 70 hours. A cross-section cut through each sample is shown in Exhibit 2.2-58. The shaded portion of the sample shows that the Monofrax L was more severely eroded than the Monofrax M*. These results are consistent with the crucible slag tests. The corrosive effects of the slag on the refractories in the laboratory tests were more severe than those observed in the RAH furnace. This may be due in part to higher temperatures in the laboratory tests.

* This is discussed further in the section by UNDEERC on the tests performed in the dynamic slag testing facility.

Exhibit 2.2-56A
Electron Probe Element Maps of Sections Through Monofrax L Crucible Shown in Exhibit 2.2-55, Containing Illinois No. 6 Slag at 2640 °F (1450°C) for 100 hours in Air

Exhibit 2.2-56B
Electron Probe Element Maps of Sections Through Monofrax M Crucible Shown in Exhibit 2.2-55, Containing Illinois No. 6 Slag at 2640°F (1450°C) for 100 hours in Air

Exhibit 2.2-57
Front View of Monofrax L and M Test Specimens Exposed to Flowing Illinois
No. 6 Slag at 2732°F (1500°C) for 70 Hours

Exhibit 2.2-58
Eroded (Shaded) Portion of Monofrax L (A) and Monofrax M (B) Test Specimens Shown in Exhibit 2.2-57

Laboratory- and Bench-Scale Activities

Bench-Scale Activities

Investigation continued this quarter into the shrinkage problems experienced with the Plicast 99 refractory material. In the last quarter, it was reported that examination of the sample of Plicast 99 refractory that contained organic fibers (which are added to allow steam to escape during firing) showed permanent shrinkage of 2.0% and 2.1%, and the sample that did not contain fibers had a permanent shrinkage of 0.7%. Repeat dilatometer measurements were made to verify the initial tests on the sample of Plicast 99 that contained no fibers. These measurements showed the permanent shrinkage ranging from 0.7% to 3.3%. The large range of values is possibly due to the sampling method used.

A sample was randomly taken from the finer raw material, then mixed with 6.7% water. This mixture was poured into a mold and allowed to dry for 24 hr. None of the larger aggregate was included, so sintering, hence permanent shrinkage, was greater than would occur if more of the aggregate were included. The dilatometer test was repeated on Plicast 99 without fibers using a sample cut from a larger green block that included the larger aggregate, and the permanent shrinkage was approximately 1.4%.

Two blocks of Plicast 99 were subjected to a 40-hr corrosion test at 2732°F (1500°C) in the bench-scale dynamic slagging application furnace, using Coal Creek slag from the first lignite run in the SFS combustor. The test was designed to determine the relative corrosion rate caused by the lignite slag, as well as to determine the effect of refractory sintering temperature and time on the corrosion resistance of the refractory. One of the blocks was fired to 2910°F (1600°C) over a

period of 24 hr, held for 24 hr, and then slowly ramped down to room temperature. The second block was fired to 2732°F (1500°C) over a 24-hr period and held for 2 hr (this has been the current method for the previous studies), and then the slag feed was started.

Exhibit 2.2-59 is a photograph showing a cross section of the block fired to 2910°F (1600°C) that was saturated with slag. After two heatup and cooldown cycles, a large expansion crack formed on the back of the refractory block, Exhibit 2.2-60. Scanning electron microscopy and x-ray diffraction analyses were done to identify any new mineral phases present in slag that penetrated the block and to look for structural changes.

Exhibit 2.2-59
Photograph Showing a Cross Section of the Plicast 99 Block that was Fired to 2910 °F (1600 °C) and became Saturated with Coal Creek Slag

Exhibit 2.2-60

Photograph Showing Large Expansion Crack that Formed on the Back of the Plicast 99 Block that was Fired to 2910 °F (1600 °C) and became Saturated with Coal Creek Slag

The major crystalline phases identified in the penetrated slag were corundum (Al_2O_3), and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), with minor amounts of mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), hercynite (FeAl_2O_4), and nepheline (NaAlSiO_4). It is believed that either the formation of these crystals or their higher coefficients of thermal expansion relative to the Plicast 99 caused the brick to crack. The Plicast

99 block that was fired to 2732°F (1500°C) also became saturated with slag, but did not develop the expansion cracks. Possibly because of the lower sintering temperature, this block started to deform plastically as shown in Exhibit 2.2-61. The block became so deformed at the top that slag was no longer flowing down the prepared vertical channel. Instead, a new channel had been created to the side of the prepared channel. A second 40-hr corrosion test was done on a Plicast 99 block fired to 2910°F (1600°C) using the Coal Creek slag. The results were similar the block became saturated with slag and developed several expansion cracks. This led to the conclusion that Plicast 99 is not the right material to use with lignite slag.

Exhibit 2.2-61
Photograph Showing Plicast 99 Block that was Fired to 2732 °F (1500 °C) Deformed Plastically when it became Saturated with Coal Creek Slag

In an effort to understand why the blocks became saturated with slag, porosity measurements using American Society for Testing and Materials (ASTM) procedure C 20-92 were made on the blocks. Blocks of Plicast 99 that did not originally contain organic fibers and had been fired to 2910°F (1600°C) showed that the average apparent porosity of the fired material is 21%. Several pieces of refractory from the SFS lining will also be subjected to the same ASTM procedure to determine if porosity measurements are comparable to the lab-scale porosity numbers.

In an attempt to reduce the amount of slag penetrating into the Plicast 99, a variety of paint-on coatings will be tested in the next quarter. These coatings should reduce the surface porosity by filling in the surface pores and creating a hard, impermeable layer, which should reduce the amount of slag infiltration. A total of eight paint-on coatings will be tested in a 100-hr static corrosion test using Illinois No.6 slag from the Baldwin Plant. Five of the paints are commercially available. Four are chrome-based paints with different additives obtained from Amertech. The fifth is a zirconia paint from ZYP Incorporated. The other three coatings are experimental mixtures made at the EERC.

A 100-hr dynamic corrosion test at 2732°F (1500°C) was started on blocks of fused-cast Monofrax L and Monofrax M, using the Coal Creek slag. To date, we have completed 60 hr of slag feed. The average measured recession is 0.14 and 0.17 in. (0.36 and 0.43 cm) for Monofrax L and M, respectively. Exhibit 2.2-62 is a graph showing that the L material stands up much better to lignite slag corrosion than it does to Illinois No.6 slag. Monofrax M stood up well in both instances, as can be seen in Exhibit 2.2-63. The remaining 40 hr will be completed in late September.

Exhibit 2.2-62
Graph Comparing Surface Recession with Time for Monofrax L using Illinois No. 6 Slag and Coal Creek Slag

Exhibit 2.2-63

Graph Comparing Average Surface Recession with Time for Monofrax M using Illinois No. 6 Slag and Coal Creek Slag

The refractory lining was removed from the SFS combustor, and slag penetration was measured at approximately six locations on several blocks from each level. These measurements were averaged and plotted on a graph, Exhibit 2.2-64, to show the approximate slag penetration from the top of the combustor to the bottom. The levels are identified by numbers from 1 to 15, with the top level being 1 and the bottom 15. The drop in slag penetration at Level 5 is due to measurements being made on two very large pieces of refractory from the door of the combustor, which was a fairly new batch of refractory.

Exhibit 2.2-64
Graph Comparing Average Slag Penetration for each Level of the SFS Combustor

Task 6 HIPPS Commercial Plant Design Update

HIPPS Repowering

Site Selection

The Electric Power Research Institute was contacted and their assistance requested in locating a utility or other coal-fired power generator who would be willing to serve as a host for a conceptual design and cost estimate of a site specific repowering case. A descriptive package of information and presentation materials was prepared to brief EPRI and interested power generators. The issue has been discussed with EPRI's Upgraded Coal Users' Group, and others. This activity is ongoing at this time.

Cycle Analysis

The emphasis in the repowering effort is to identify HIPPS power generation cycles with efficiencies comparable to those realized by the Advanced Turbine System (ATS) Program (~60% LHV). Of course the HIPPS would use coal as the majority fuel (>50%) and would be aimed at eventual application to repowering. It should be noted that the industry convention is to use lower heating value (LHV) to define efficiency for power cycles using gaseous and liquid fuels (e.g., ATS) while solid fuel power systems efficiencies (e.g., HIPPS) are based on higher heating value (HHV). For methane, the difference between LHV and HHV is approximately 10%; for natural gas (mainly methane), 9.5 %, and for coal, approximately 4%. For the HIPPS, which burns a combination of coal and natural gas, the difference is a function of the coal/gas ratio. For the HIPPS, the values range from 5% to 7%. These differences tend to confuse the comparison of coal-based and gas-based power system efficiencies.

Previously, a Cascaded Humidified Advanced Turbine (CHAT) system had been identified with an efficiency over 56% HHV or approximately 60% LHV. See column 4 in Exhibit 6-1. The CHAT cycle is essentially a reheat HAT cycle with a turbo-compressor (T-C) set introduced to raise the over cycle pressure ratio thereby allowing a higher mass of water vapor in the compressor discharge fuel. When used in a cycle with a frame-type gas turbine, the T-C set can replace part of the large turbines compressor resulting in a cycle with a higher pressure ratio and reduced compressor work on the frame engine. Some problems of flow matching can also be avoided. When used with an aeroderivative gas turbine, especially one which is already at high pressure and intercooled, the CHAT loses much of its thermodynamic attractiveness. However there could be some added benefit in the HIPPS because of the desire to keep the pressure in the high temperature heat exchangers as low as practical. The CHAT also introduces extra equipment (T-C set and added heat exchangers and combustors) to the relatively simple HAT cycle configuration. With this in mind, additional work was done on a HAT cycle to identify higher efficiency configurations.

The HAT configuration selected is shown in Exhibit 6-2. It is based on the configuration first identified in the Phase 1 of the ATS Program. The turbine has been updated to reflect the changes in the FT4000 that have been made between the 1993 study and the present. For convenience, a baseline FT4000 ICAD and the gas-fired HAT are also shown in Exhibit 6-1. Improvements to the FT4000 ICAD include more extensive use of ceramic components and the

use of a convectively cooled combustor. Some advances in blade cooling area also applied. The result is a gas-fired HAT with reheat having an estimated efficiency of 63.8% (HHV). This compares to the original ATS reheat HAT efficiency of 62.7% (HHV). When this engine version is integrated into the HIPPS, a system with an gross efficiency of 56.8% (HHV) or 61.0% (LHV) results. The net LHV efficiency would be 60.25%., easily comparable to the ATS efficiencies.

Exhibit 6-1 Comparison of HAT Cycles

Type of fuel	PW Nat Gas	METC Gas	AHIPS Gas/ Coal	CHAT Gas/ Coal
System Performance				
Total net power, MW	144.0	414.9	404.8	316.0
Gross Gas Turbine power, MW	146.9	419.1	409.6	290.0
Cycle Efficiency, net (HHV)		57.0	56.1	54.9
Cycle Efficiency, Gross (HHV)		57.6	56.8	55.5
Cycle Efficiency, gross (LHV)	45.8	63.8	61.0	59.6
Gas/Coal Ratio	1.0	1.0	0.5	0.5
Gas Turbine Performance				
GT HPT temp, F	----	3060	3060	3060
GT LPT temp, F	----	2579	2556	2555
GT Reheat in, F		2326	2320	2354
GT power turbine temp, F	----	2500	2500	2450
GT exhaust temp, F	721	1200	1184	1193
GT stack temp, F	721	120	120	120
Turbine Cooling (% Inlet)	----	----	18.7	18.9
Gas Fuel flow rate, lbs./sec	14.4	29.5	15.5	11.8
Saturator flow rate, lbs./sec	0.0	178.0	186.1	131.1
Saturator outlet temp, F	NA	399	401	410
HITAFF Combustor				
Coal flow rate, lbs./sec	NA	NA	29.9	24.6
Convective HX outlet temp, F	NA	NA	1473	1464
Radiant HX outlet temp, F	NA	NA	2100	2100

Exhibit 6-2
Simplified HIPPS/HAT