FINAL

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

DE-AC22-95PC95144

Quarterly Progress Report

October 1, 2000 – December 31, 2000

Prepared for

Federal Energy Technology Center
Pittsburgh, Pennsylvania

United Technologies Research Center
411 Silver Lane, East Hartford, Connecticut 06108

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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) ≥ 47%

NOx, SOx, and particulates ≤ 10% NSPS
(New Source Performance Standard)

coal providing ≥ 65% of heat input

all solid wastes benign

cost of electricity ≤ 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.

Phase II, had as its initial objective the development of a complete design base for the construction and operation of a HIPPS prototype plant to be constructed in Phase III. As part of a descoping initiative, the Phase III program has been eliminated and work related to the commercial plant design has been ended. The rescoped program retained a program of engineering research and development focusing on high temperature heat exchangers, e.g. HITAF development (Task 2); a rescoped Task 6 that is pertinent to Vision 21 objectives and focuses on advanced cycle analysis and optimization, integration of gas turbines into complex cycles, and repowering designs; and preparation of the Phase II Technical Report (Task 8). This rescoped program deleted all subsystem testing (Tasks 3, 4, and 5) and the development of a site-specific engineering design and test plan for the HIPPS prototype plant (Task 7).

Work reported herein is from:

Task 2.2 HITAF Air Heaters

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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:

≥ 47% thermal efficiency (HHV)

NOx, SOx, and particulates ≤ 10% NSPS

coal providing ≥ 65% of heat input

all solid wastes benign

cost of electricity ≤ 90% of present plant

Work reported in this report is from Task 2.2 HITAF Air Heaters, and Task 2.4 Duct Heater and Gas Turbine Integration.

Task 2.2 HITAF Air Heaters

The following summarizes the results and observations from the September, 2000 natural gas-fired test.

<u>Task 2.2.4 – Pilot-Scale Testing</u>

Data and observations from an SFS natural gas-fired test completed September 19–21, 2000, are documented in this report and compared with previous data where appropriate. The primary purpose of the test was to evaluate the performance of the radiant air heater (RAH) panel without ceramic tiles to protect the heat-transfer surfaces from furnace conditions. An additional objective was to identify any system limitations, such as process air capacity, that need to be addressed so that the RAH can be operated without the ceramic panels while coal is fired.

In September, the Kyocera tiles were removed from the RAH panel. Removal of the tiles was necessary for two reasons. First, the Kyocera tiles exhibited extensive cracking following the June SFS test as a result of two thermal cycles in the furnace. It is suspected that these cracks were present upon installation but were not visible. These hairline cracks are believed to form as a result of the fabrication steps (casting, cooling process, and machining), while thermal cycling is believed to be the primary cause of crack propagation for both the Monofrax M and Kyocera tiles. Therefore, based on the condition of the Kyocera tiles, further tests with the tiles were not warranted.

Removal of the tiles was also necessary to permit one final natural gas-fired SFS test evaluating the performance of the RAH panel without tiles in place to protect the MA 754 alloy surfaces from furnace conditions. The furnace firing rate and exit temperature were limited to avoid overheating the MA 754 alloy surfaces. The data, results, and observations in this report were not available for inclusion in the July through September quarterly technical progress report.

Observations from the September natural gas fired test include:

1) The high-density refractory lining the furnace was found to be in excellent condition following the September test. No refractory color change occurred as a result of natural gas firing.
2) The slagging furnace heating rate during the September test period was limited to 100°F/hr (56°C/hr) to protect the RAH and the main burner firing rate was controlled to prevent the MA754 alloy surfaces from being overheated for a range of RAH process air flow rates.
3) The main burner accounted for 100% of the fuel fired and performed well during the September test.
4) Process air temperature and flow rate were adequate to support operation of the CAH tube bank. However, the process air flow rate capacity available to support the RAH panel limited the firing rate of the combustor and the resulting combustor temperature.
5) The lower level of heat recovery observed in September was directly related to the lower flue gas temperature and flow rate to which the CAH tube bank was exposed as a result of furnace firing rate.
6) Tube surface temperatures in September were comparable to those for all previous coal-fired tests near the process air outlets because, for a given process air flow rate, because the furnace firing rate was adjusted to maintain tube surface temperatures at these locations near limits established for the MA754 alloy.
7) Heat recovery with natural gas firing is impressive vis-a-vis coal firing given the fact that the coal-fired data with tiles represents furnace temperatures ranging from 2700° to 2950°F (1482° to 1621°C) while the natural gas-fired data without tiles represents a furnace temperature of 2300°F (1260°C).

Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through December 2000

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	2075	1545	3620
CAH Tube Bank	1760	1512	3272
RAH Panel	1472	1465	2937

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

Pilot-scale activities this past quarter involved SFS maintenance and repairs following completion of a short natural gas-fired SFS test in September, completion of data evaluation and preparation of data summaries resulting from the September SFS test, and the initiation of work on the program's final project report. Instrumentation work this past quarter focused on routine maintenance and calibration of SFS components.

Description of Pilot-Scale SFS

Exhibit 2.2-1 is a simplified illustration of the overall slagging furnace system. There have been no changes to the exhibit in the past quarter.

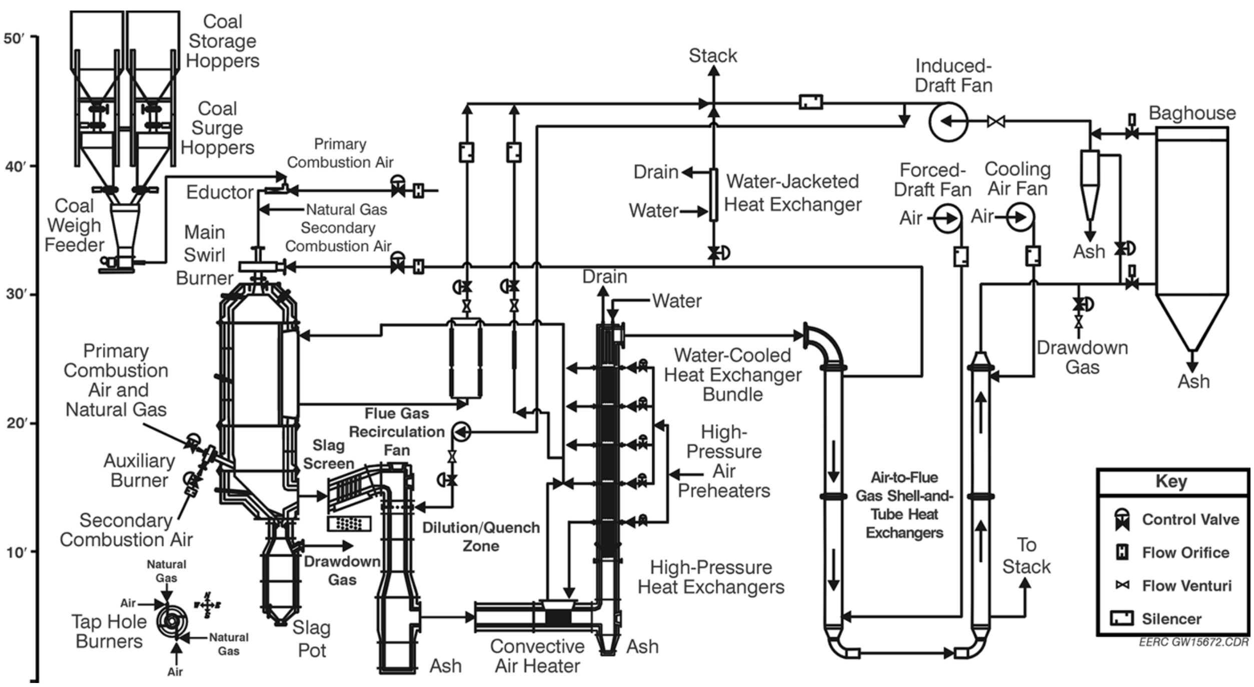

Exhibit 2.2-1
Combustion 2000 Slagging Furnace and Support System

Slagging Furnace

The pilot-scale slagging furnace is intended to be as fuel-flexible as possible, with maximum furnace exit temperatures of 2700°F to 2900°F (1482°C to 1593°C) to maintain the desired heat transfer to the RAH panel and slag flow. The furnace 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 Illinois No. 6 bituminous coal (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 645 scfm (12.0 to 18.6 m^3/min), with a nominal value of 530 scfm (15 m^3/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 furnace is orientated vertically (downfired) and the burner design is based on that of a swirl burner used on two smaller EERC pilot-scale pulverized coal (pc)-fired units (600,000 Btu/hr [633,000 kJ/hr]). Slagging furnace internal dimensions are 47 in. (119 cm) in diameter by roughly 16 ft (4.9 m) in total length.

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 are made using two Type S thermocouples protruding 1 in. (2.5 cm) into the furnace through the refractory wall and three optical pyrometers (flame, flue gas along the furnace wall near the RAH panel, and flue gas at the furnace exit). Furnace temperature is also measured using thermocouples located at the interface between the high-density and intermediate refractory layers as well as between the intermediate and insulating refractory layers. A pressure transmitter and gauges are used to monitor static pressures in order to monitor furnace performance. These data (temperatures and pressures) are automatically logged into the data acquisition system and recorded manually on data sheets on a periodic basis as backup.

The slag tap is intended to be as simple and functional as possible. To that end, the design is a simple refractory-lined hole in the bottom of the furnace. The diameter of the slag tap is nominally 4 in. (10 cm), with a well-defined drip edge. A two-port natural gas-fired taphole burner is used to maintain slag tap temperature for good slag flow. To minimize heat losses, slag is collected in an uncooled, dry container with refractory walls. When the slag tap had plugged in the first couple years of the project, the plug was typically removed on-line after a switch was made to natural gas firing for a short period of time (2 hr) in the main burner. In early 1999, an approach was developed and personnel safety equipment acquired to permit the removal of slag tap plugs on-line while coal is fired. Because no coal firing occurred during the September test period, slag tap plugging was not an issue, and slag pot removal and maintenance following the test were not necessary.

The refractory walls in the slagging furnace are composed of three layers of castable refractory. They consist of:

- an inner 4-in. (10.2-cm) layer of high-density (14-Btu-in./ft^2°F-hr or 2.0-W/m-K) slag-resistant material;
- 4 in. (10.2 cm) of an intermediate refractory (4.0 Btu-in./ft^2°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./ft^2°F-hr or 0.2 W/m-K).

Three refractory layers were selected as a cost-effective approach to keeping the overall size and weight of the furnace to a minimum while reducing slag corrosion and heat loss. Table 2.2-1 summarizes properties for refractory material used in the SFS. The condition of the high-density refractory in the furnace was excellent following the test completed in September 2000. Natural gas firing in the furnace has no visible impact on furnace refractory as long as the flame does not impinge on it.

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, which uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl. Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NO_x. Carbon conversion has been >99% when bituminous and subbituminous coal and lignite are fired. High carbon conversions can be obtained at low swirl settings because of the high operating temperature and adequate residence time. Combustion air flow rates through the main burner range from about 400 to 600 scfm (11 to 17 m^3/min), depending on furnace firing rate and the fuel type (bituminous, subbituminous, or lignite) fired.

Table 2.2-1
Refractory Properties

Refractory:	**Plicast Cement- Free 99V KK/99V**[1]	**Plicast Cement- Free 98 KK/98**[1]	**Plicast Cement- Free 96V KK/96V**[1]	**Narco Cast 60**	**Plicast LWI-28**	**Plicast LWI-20**	**Harbison - Walker 26**
Function	**High density**	**High density**	**High density**	**High density**	**Insulating**	**Insulating**	**Insulating**
Service Limit, °F	3400	3400	3300	3100	2800	2000	2600
Density, lb/ft^3	185	185	185	145	80	55	66
K, Btu-in./ft^2°F-hr @ 2000°F	14.5	14.5	14.0	6.5	4.0	NA[2]	2.2
K, Btu-in./ft^2°F-hr @ 1500°F	14.7	14.7	14.2	6.0	3.0	1.7	1.9
K, Btu-in./ft^2°F-hr @ 1000°F	15.5	15.5	15.0	5.6	2.7	1.3	.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_2O_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_2O_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.

An auxiliary gas burner (maximum firing rate of 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 panel. 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 Panel

A key design feature of the furnace is accessibility for installation and testing of an RAH panel. The furnace will accept a panel with a maximum active size of 1.5 × 6.4 ft (0.46 × 1.96 m). This size was selected on the basis of panel-manufacturing constraints identified by UTRC as well as a desire to minimize furnace heat losses. Flame impingement on the RAH panel is not necessarily a problem. Process air for the RAH panel is provided by an air compressor having a maximum delivery rate of 510 scfm (14.4 m^3/min) and a maximum stable delivery pressure of 275 psig (19 bar). Backup process air is available from a smaller compressor at a maximum delivery rate of 300 scfm (8.5 m^3/min) and pressure of <100 psig (<7 bar). A tie-in to a nitrogen system is also available as a backup to the air compressor system. In the event of a failure of inlet process air piping, a backflow emergency piping system was installed so that overheating of the RAH panel could be avoided.

Slag Screen

The slag screen design for the pilot-scale SFS is the result of a cooperative effort between EERC, UTRC, and PSI personnel. The primary objective for the pilot-scale slag screen is to reduce the concentration of ash particles entering the convective air heater (CAH). The walls of the slag screen consist of two refractory layers. The inner, high-density layer is a Plicast Cement-Free 98V 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 refractory selected for use in the slag screen are summarized in Table 2.2-1.

The current slag screen design permits the use of a maximum of 18 tubes, 1.5 in. (3.8 cm) in diameter in a six-row staggered array. The number of tubes in use for a given SFS test is dependent on the ash fusion properties of the fuel ash. 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 during this quarter are addressed later in this report.

Dilution/Quench Zone

The dilution/quench zone design was a cooperative effort between the EERC and UTRC. It is refractory-lined and located immediately downstream of the slag screen and upstream of the CAH duct. It is oriented vertically and has a 1.17-ft (0.36-m) inside diameter in the area of the flue gas recirculation (FGR) nozzles, expanding to 2 ft (0.6 m) below the nozzles 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.

Routine cleaning of the dilution/quench zone has been required during each weeklong coal-fired test. A pressure transmitter is used to monitor and record differential pressure, as an indication of slag deposition in the dilution/quench zone. On the basis of observations made during an August 1998 test and the frequent cleaning required, the EERC modified the spool piece section of the dilution/quench zone. The specific modification involved the addition of a water-cooled wall around the FGR nozzles. This water-cooled wall appears to embrittle the slag deposits that form in this area, making them more prone to spontaneous shedding and generally easier to remove on-line. Performance observations during the September test are summarized later in this report.

Convective Air Heater

The CAH design was a cooperative effort between the EERC and UTRC. The flue gas flow rate to the CAH tube bank has been calculated to range from 3553 to 4619 acfm at 1800F (101 to 131 m^3/min at 982C). A rectangular inside duct dimension of 1.17 ft^2 (0.11 m^2) 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 were uncooled ceramic material, with the remaining seven tubes cooled by heated process air. The uncooled ceramic tubes were replaced in May 1998 with uncooled stainless steel tubes because the ceramic tubes were repeatedly damaged when the tube bank was removed from the duct.

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 2.2-2 illustrates the original position, size, and alloy type for the five uncooled tubes. At the request of UTRC, two of these uncooled alloy tubes were removed from the CAH tube bank following a September 1999 test and returned to UTRC for characterization. The tubes removed from the CAH represent the alloys designated Incoloy MA956HT and Incoloy MA956. Replacement tubes were fabricated using 1.5-in. (3.8-cm) Schedule 40 stainless steel pipe prior to a December 1999 test. No additional changes were made to the CAH this past quarter. Exhibit 2.2-3 illustrates the position, size, and alloy type for the CAH tubes in place during the December 1999 and March, June, and September 2000 SFS tests.

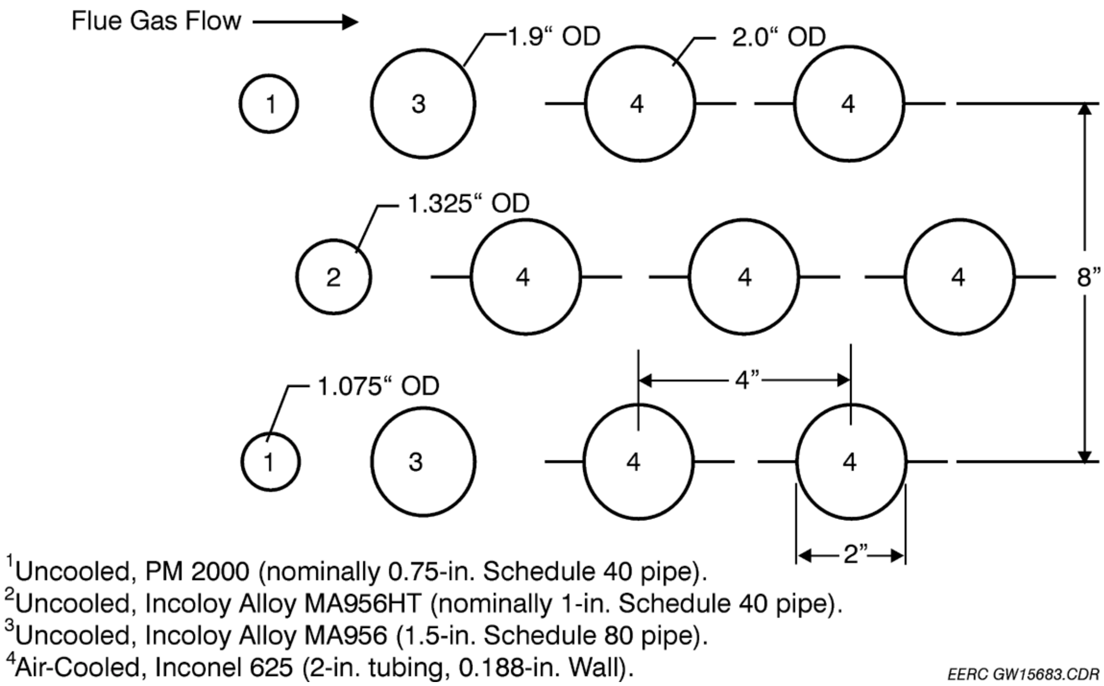

Exhibit 2.2-2
Illustration of the Tubes in the CAH Tube Bank Prior to a December 1999 SFS Test

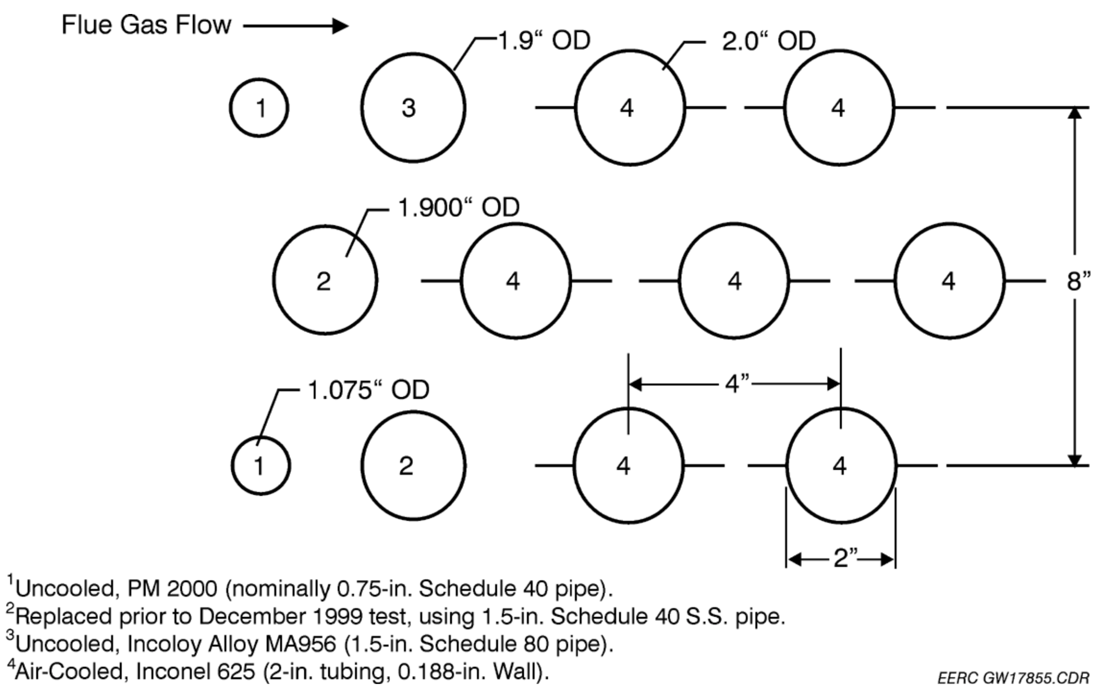

Exhibit 2.2-3
Illustration of the Tubes in the CAH Tube Bank for the September 2000 SFS Test

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 20 in. W.C. (37 mm Hg).

During the past quarter, the tube sheet used permitted the installation of 36 bags arranged in a six-by-six array. Bag dimensions are nominally 6 in. (15.2 cm) in diameter by 10 ft (3.0 m) in length, providing a total filtration area of 565 ft^2 (52.5 m^2). The bag type being used at this time is a 22-oz/yd^2 (747-g/m^2) woven glass bag with a polytetrafluoroethylene (PTFE) membrane. Because the test completed in September involved only natural gas firing, the pulse-jet baghouse was bypassed during the September test. Flue gas flow was diverted through a cyclone. Therefore, cleaning of the bags was not necessary, and there are no baghouse performance observations to report.

Instrumentation and Data Acquisition

The instrumentation and data acquisition components for the pilot-scale SFS address combustion air, flue gas, process air, process water, temperatures, static and differential pressures, and flow rates. The process control and 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 it reaches the analyzers. Flue gas is routinely sampled in the slag screen at the furnace exit and the exit of the baghouse. Total flue gas flow rate through the SFS is measured using a venturi. No instrumentation work was completed this past quarter other than routine maintenance and calibration.

Pilot-Scale SFS Activities

A short natural gas-fired SFS test was completed September 19-21. The purpose of the test was:

- to evaluate the performance of the RAH panel without ceramic tiles protecting the heat- transfer surfaces from furnace conditions, and
- to identify any system limitations, such as process air capacity, that need to be addressed so that the RAH can be operated without the ceramic panels while coal is fired.

As discussed in the October through December 1999 and January through March 2000 quarterly technical progress reports, laboratory tests of the coal ash and gas corrosion of the alloy used to make the RAH indicate that corrosion rates may be acceptable even if exposed directly to the products of combustion of at least some coals. If the RAH can be operated without the ceramic panels, then the cost and impedance to heat transfer caused by the panels can be eliminated. In addition, the size of the RAH and time to commercialization can be substantially reduced.

The approach involved firing the SFS on natural gas and limiting the heatup rate to 100°F/hr (56°C/hr). Thermocouples and an optical pyrometer were used to monitor the surface temperature of the MA754 alloy tubes. Alloy surface temperatures were not allowed to exceed 2000°F (1094°C). Furnace firing rate, exit temperature, and process air flow rate were controlled to prevent the MA754 alloy surfaces from being overheated. Results from the September test were not available for inclusion in the July through September quarterly technical progress report; however, data evaluation has now been completed. Therefore, the results and observations for the September test as well as SFS maintenance activities this past quarter are summarized in the following discussion.

Fuel Feed System

During the September test, adjustments to natural gas flow rate to the main burner were made to prevent the MA754 alloy surfaces in the RAH panel from being overheated. Since coal was not fed during the test, there are no detailed fuel analyses to report. However, Table 2.2-2 listing the compositions of the previous coals tested is included in this report for informational purposes. They include Illinois No. 6, three eastern Kentucky bituminous coals, Rochelle and Cordero Rojo subbituminous coals, and Coal Creek Station (CCS) and Milton R. Young Station (MRYS) lignites.

Slagging Furnace Operation

The slagging furnace heating rate during the September test period was limited to 100°F/hr (56°C/hr) while natural gas was fired, as recommended by UTRC to protect the RAH. However, rather than firing the main burner to achieve a specific furnace temperature, the main burner firing rate was controlled to prevent the MA754 alloy surfaces from being overheated for a range of RAH process air flow rates. As a result, furnace temperature was controlled in the range of 2200 to 2400°F (1205 to 1316°C). The natural gas-firing rate through the main burner was nominally 2.0 to 2.3 MMBtu/hr (1.9 to 2.4×10^6 kJ/hr). The auxiliary burner was not used during the September test. Therefore, the main burner accounted for 100% of the energy input.

Furnace temperature was established initially using two Type S thermocouple measurements and an optical pyrometer measurement. As thermocouple performance appeared to degrade, furnace temperature was measured using the optical pyrometer. A summary of furnace and slag screen temperatures is presented as a function of run time in Exhibit 2.2-4. Corresponding furnace firing rate data are summarized in Exhibit 2.2-5.

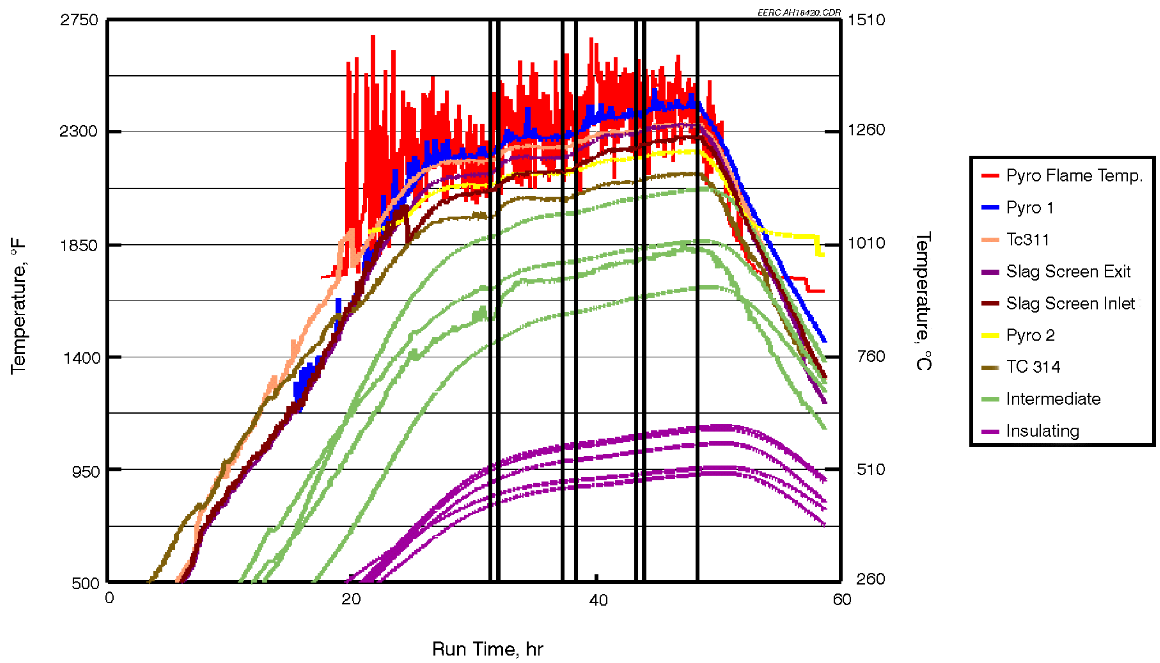

Exhibit 2.2-4
Furnace and Slag Screen Temperatures Versus Run Time for the September Test, SFS-RH14-0500

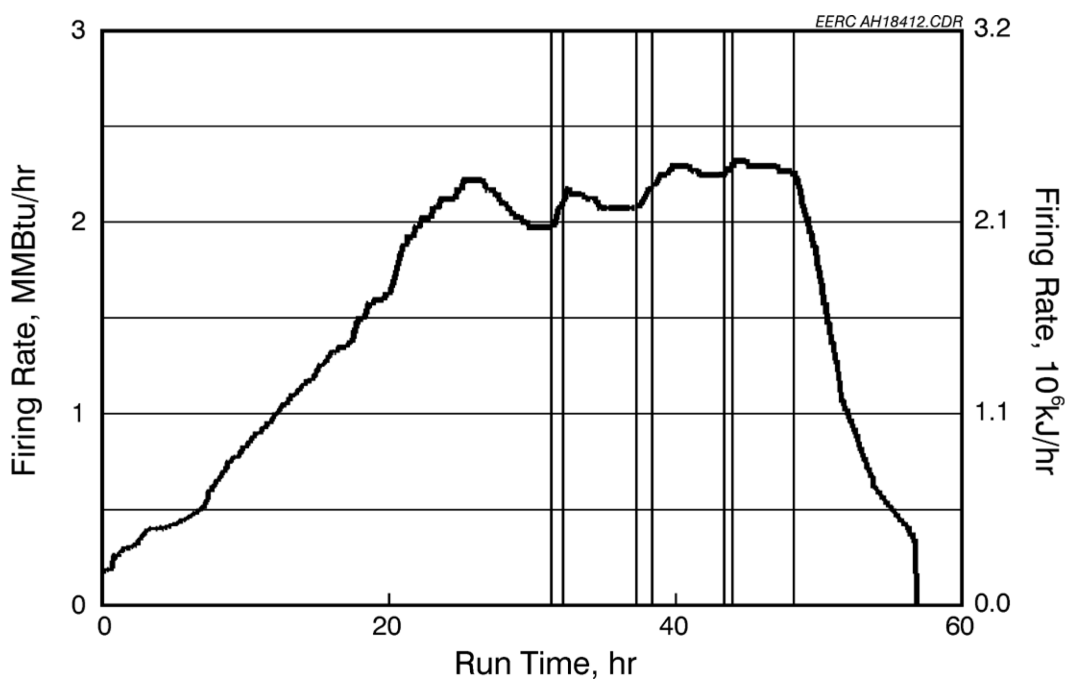

Exhibit 2.2-5
Furnace Firing Rate Versus Run Time for the September Test, SFS-RH14-0500

Furnace refractory temperatures ranged from 800 to 1120°F (427 to 605°C) for the hot side of the insulating (outer layer) refractory to as high as 2090°F (1144°C) for the cold side of the high-density (inner layer) refractory. However, as indicated by the temperature data in Exhibit 2.2-4, furnace refractory temperatures never reached equilibrium during the 3-day test because of the periodic changes made to furnace firing rate. Therefore, actual refractory temperatures would be higher than those observed during the September test if test duration would have allowed the furnace refractory to achieve equilibrium. Also, the actual furnace firing rate required to maintain a given furnace temperature in the range observed during the September test would be lower if furnace refractory was allowed to reach thermal equilibrium. Because of the nature and objectives of the September test, a comparison of furnace and refractory temperature data with previous SFS test data is not appropriate. September firing rate and furnace temperature data relative to other SFS tests is discussed in a limited manner with respect to heat recovery in the RAH panel.

Table 2.2-2
Results of Fuel and Fuel Ash Analysis for Slagging Furnace Tests[1]

	Illinois No. 6 Bituminous Coal	Kentucky Bituminous Coal	Prater Creek Bituminous Coal	High Ash Fusion Bituminous Coal[2]
Proximate Analysis, wt%				
Moisture	2.8–10.3	2.3–2.5	1.7–2.0	2.2
Volatile Matter	35.9–39.9	38.2–38.7	37.9–38.7	36.9
Fixed Carbon	43.3–46.3	54.7–54.9	54.5–55.3	53.8
Ash	10.6–11.7	3.9–4.7	4.7–5.1	7.1
Ultimate Analysis, wt%				
Hydrogen	4.7–5.8	5.2–5.5	5.3–5.4	5.1
Carbon	61.6–67.6	77.5–78.2	77.5–78.3	74.8
Nitrogen	0.8–1.9	1.8	2.3–2.4	2.3
Sulfur	3.2–4.1	0.8–1.0	0.8–0.9	0.9
Oxygen	10.6–17.6	9.6–9.7	8.4–8.7	9.8
Ash	10.6–11.7	3.9–4.7	4.7–5.1	7.1
Heating Value, Btu/lb	11,015–11,658	13,861–14,120	13,538–14,167	13,103
Percent as Oxides, wt%				
SiO_2	49.3–53.9	42.5–44.8	38.2–38.4	56.4
Al_2O_3	19.8–21.5	28.9–29.8	24.4–25.0	32.5
Fe_2O_3	13.6–17.5	13.7–14.5	22.5–23.0	4.4
TiO_2	0.9–1.0	1.1	0.9–1.0	1.9
P_2O_5	0.1–0.2	0.1	0.1–0.2	0.1
CaO	2.6–3.6	1.9–2.8	3.6–3.8	0.8
MgO	1.5–2.0	2.2–2.4	1.9–2.1	1.3
Na_2O	1.1–1.5	1.1–1.3	0.3–0.6	0.3
K_2O	1.9–2.3	2.7–3.0	2.2–2.3	2.0
SO_3	2.5–4.0	2.4–3.8	4.6–4.9	0.2
Ash Fusion Temp., °F				
Initial	2315–2392	2398–2577	2474–2483	>2800
Softening	2342–2418	2440–2603	2490–2501	>2800
Hemisphere	2392–2448	2474–2621	2532–2544	>2800
Fluid	2491–2593	2588–2684	2571–2593	>2800
Sieve Analysis				
Screen Mesh Size	Weight Percent Retained			
100	1.8–25.2	8.1–11.4	13.6–14.9	9.8
140	0–14.9	12.9–13.9	10.4–15.1	8.1
170	0–14.9	NA[3]	NA	NA
200	9.6–13.5	11.4–13.5	12.4–12.9	11.6
230	0–16.2	8.7–9.4	8.0–8.3	8.7
270	0.5–14.6	0.7–1.6	0.8–1.2	1.9
325	7.4–14.7	11.9–12.7	10.9–11.9	12.0
400	0–4.7	NA	NA	NA
Pan	29.7–57.8	41.2–42.6	38.8–40.7	47.9
Total %	99–100.2	99.9–100.1	99.9–100.0	100.0

[1]Analysis is presented on an as-fired basis.
[2] This fuel was not successfully fired in the SFS. [3] Not available.

Table 2.2-2 (continued)

	Cordero Rojo Subbituminous Coal	Rochelle Subbituminous Coal	Coal Creek Station Lignite	Milton R. Young Station Lignite
Proximate Analysis, wt%				
Moisture	25.3–26.1	21.6–24.3	31.6–37.9	33.8–37.1
Volatile Matter	35.8–36.5	35.6–37.4	29.4–31.5	30.4–32.1
Fixed Carbon	32.7–32.9	35.8–36.7	26.4–26.8	26.9–27.9
Ash	5.3–5.4	4.3–4.7	6.3–10.2	5.6–6.2
Ultimate Analysis, wt%				
Hydrogen	6.3	6.1–6.4	6.4–6.8	7.0–7.2
Carbon	49.4–49.7	53.0–55.2	38.5–40.9	41.1–43.4
Nitrogen	1.2	0.6–0.7	0.6	0.6
Sulfur	0.45	0.3	0.5–0.7	0.7–0.9
Oxygen	37.1–37.2	32.9–33.4	41.1–47.3	42.1–44.9
Ash	5.3–5.4	4.3–4.7	6.3–10.2	5.6–6.2
Heating Value, Btu/lb	8818–8853	9021–9328	6300–6708	6933–7144
Percent as Oxides, wt%				
SiO_2	26.7–26.8	26.7–27.1	31.8–35.5	11.2
Al_2O_3	17.1–17.5	15.5–16.3	11.7–12.0	8.6
Fe_2O_3	6.8–7.2	6.3–6.6	6.4–8.0	13.2
TiO_2	1.6	1.2–1.4	0.5	0.2
P_2O_5	1.1	0.7–0.9	0.3	0.1
CaO	26.1–26.2	21.6–24.3	17.0–18.7	21.3
MgO	5.2	6.7–6.9	6.5–7.0	7.3
Na_2O	1.0	1.5	2.9–3.2	11.7
K_2O	0.3–0.4	0.1–0.4	1.3	0.2
SO_3	13.4–13.7	15.6–17.0	16.0–19.0	26.2
Ash Fusion Temp., EF				
Initial	2221	2202–2295	2170–2188	2370–2371
Softening	2250–2251	2205–2308	2181–2196	2381–2384
Hemisphere	2262–2266	2214–2311	2189–2203	2384–2387
Fluid	2286	2221–2325	2196–2219	2392–2428
Sieve Analysis				
Screen Mesh Size		Weight Percent Retained		
100	11.0–13.5	7.6–8.8	6.4–10.3	14.9
140	15.0–15.1	14.2–15.4	12.3–13.8	15.7
170	NA[3]	NA	NA	4.6
200	13.3–14.2	14.3–14.4	11.9–12.3	8.5
230	8.0–9.0	8.4–9.1	3.7–8.5	NA
270	2.2–2.9	2.0–5.6	6.2–10.2	3.1
325	9.4–11.0	4.8–11.6	6.4–6.5	14.9
400	NA	NA	NA	NA
Pan	37.6–38.0	39.7–43.4	41.5–48.2	38.2
Total %	100.0–100.2	98.6–100.6	98.3–99.9	99.9

[1] Analysis is presented on an as-fired basis.
[2] This fuel was not successfully fired in the SFS.
[3] Not available.

The high-density refractory lining the furnace was found to be in excellent condition following the September test. No refractory color change occurred as a result of natural gas firing. High-density refractory color changes are consistently observed as a result of coal firing as slag penetrates the surface of the refractory.

Main and Auxiliary Burners

The main burner performed well during the September test. As previously stated, the main burner accounted for 100% of the fuel fired and burner swirl was maintained at 20% or less. The auxiliary burner was not used during the September SFS test. However, a small quantity of air was fed through the auxiliary burner to prevent overheating of burner components. On the basis of operating experience, the EERC intends to continue minimum main burner swirl as necessary to establish a stable flame in order to maintain uniform temperatures over the length of the furnace and minimize NO_x emissions. Future auxiliary burner use will depend on the desired furnace temperatures and ash characteristics for any given SFS test, but will be minimized whenever possible.

Slag Screen

Although in poor condition, the slag screen was intact following the June 2000 test. Therefore, no modifications were made to the slag screen before the natural gas-fired test in September. Slag screen flue gas temperatures based on thermocouple measurements during the September test were 2060 to 2350°F (1127 to 1288°C). These measured temperatures are believed to be less than the actual flue gas temperatures because the thermocouples are located behind individual water-cooled slag screen tubes. Also, with time, the thermocouples are observed to deteriorate as a result of slag attack when coal is fired. Typically, slag screen operating temperature is selected on the basis of ash fusion data for the fuel to be fired. To ensure slag flow from the slag screen to the slag tap, the slag screen is operated at flue gas temperatures of 100 to 200°F (56 to 112°C) above the fluid temperature of the fuel ash. However, since coal firing did not occur in September, slag screen temperature was simply allowed to follow furnace temperature.

In October, the slag screen was removed from the SFS and rebuilding was begun of the internal surface subsequent to its use in support of the SFS tests in June and September 2000. The reconstruction effort was completed in November. The work involved replacing damaged refractory and installing three rows of tubes. Three rows of tubes were selected because the EERC expects that future tests with the SFS will initially involve firing a high-ash-fusion-temperature bituminous coal. Based on slag screen operating experience when this fuel type is fired, future tests would require the use of refractory-covered 0.38-in. (0.95-cm) stainless steel water-cooled tubes in the first row and refractory-covered 0.25-in. (0.64-cm) water-cooled stainless steel tubes in the second and third rows (nine tubes total).

Slag screen plugging and differential pressure control were nonissues while natural gas was fired in September, as was slag tap performance. The natural gas-fired tap burners were not used, and slag tap temperature was allowed to follow furnace temperature. Because furnace operation was limited to firing natural gas, no mass balance data were available.

Dilution/Quench Zone

Slag deposits did not form in the vicinity of the FGR nozzles during the September test because furnace operation was limited to natural gas firing. Therefore, it was not necessary to clean the area of the FGR nozzles on a periodic basis, and there was no ash observed on the refractory walls downstream of the FGR nozzles.

Process Air Preheaters

The process air for the CAH tube bank and the RAH panel is preheated using tube bundles downstream of the CAH. Further heating of the process air entering the RAH panel is achieved electrically. Process air for the CAH tube bank is supplied by the first process air preheater tube bundle. During the September test, process air entering the CAH tube bank was not controlled at a specific temperature set point because test conditions were dictated by the RAH panel. As a result, the temperature of the process air entering the CAH ranged from 915 to 1060°F (490 to 570°C) for nominal process air flow rates of 100 scfm (2.8 m^3/min). Process air temperatures at the exits of the other four preheater tube bundles were nominally 990 to 1080°F (532 to 582°C) for combined flow rates totaling 50 to 170 scfm (1.4 to 4.8 m^3/min). These process air temperatures are lower than typically observed because of the lower furnace-firing rate, which resulted in a lower flue gas flow rate and temperature.

Process air preheater temperatures are shown as a function of run time in Exhibit 2.2-6. The temperature data indicate that the process air temperature increased as furnace firing rate and flue gas flow rate increased. Heat-transfer rate did not degrade as a function of time because natural gas firing did not result in the formation of ash deposits on the tube surfaces. Process air temperature and flow rates were adequate to support operation of the CAH tube bank. However, the process air flow rate capacity available to support the RAH panel limited the firing rate of the combustor and the resulting combustor temperature. These issues will be discussed in more detail later in the report.

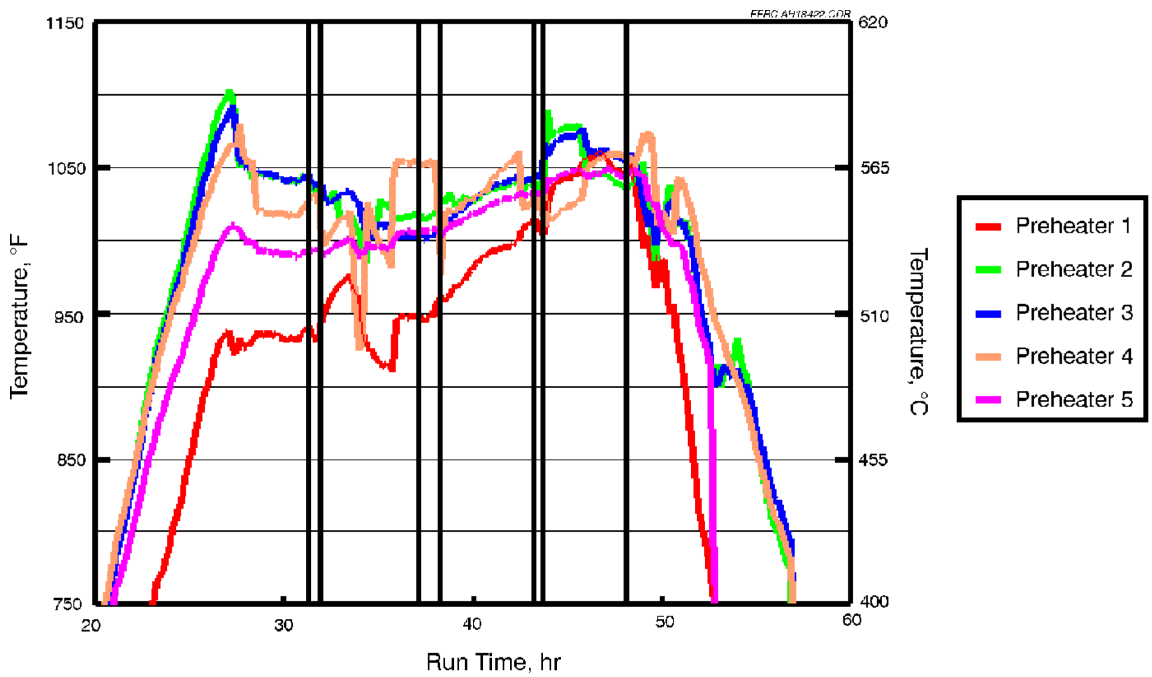

Exhibit 2.2-6
Process Air Preheater Temperatures Versus Run Time for the September Test, SFS-RH14-0500

Emission Control

During gas-fired furnace operation in September, the pulse-jet baghouse was bypassed with flue gas flow diverted through the cyclone. Therefore, there are no baghouse data to report. Measured flue gas flow rate was nominally 620 scfm (17.6 m^3/min).

Table 2.2-3 shows the average flue gas composition measured during the September test. The O_2, CO, and CO_2 data are based on furnace exit measurements made in the slag screen outlet. The CO concentrations in the slag screen were nominally 10 to 20 ppm during the September test. These values are comparable to those observed for other natural gas-fired periods during previous SFS tests. CO concentration at the baghouse outlet sampling location was 6-8 ppm, indicating that most of the CO observed in the slag screen was oxidized in the dilution/quench zone and CAH section. These measured CO concentrations indicate that some combustion was taking place in the slag screen and most likely in the dilution/quench zone and CAH section as well. This observation is supported by the lower O_2 and higher CO_2 concentrations observed at the exit of the baghouse when compared to the slag screen location.

Table 2.2-3
Flue Gas Composition for the Natural Gas-Fired SFS Test

	Concentration	lb/MMBtu
O_2	6.7%–8.7%	–
CO_2	7.3%–8.6%	–
CO	10–20 ppm	–
NO_x	NA	NA
SO_2	NA	NA

NO_x and sulfur dioxide concentrations in the flue gas were not measured during the September SFS test. Therefore, there are no data to discuss.

Testing of the CAH Tube Bank

Exhibits 2.2-7 through 2.2-9 summarize CAH tube bank surface and flue gas temperatures, process air temperatures, and process air flow rate data for the June test. Exhibit 2.2-10 illustrates the location of thermocouples in the CAH tube bank, and Table 2.2-4 presents a list of thermocouple descriptions.

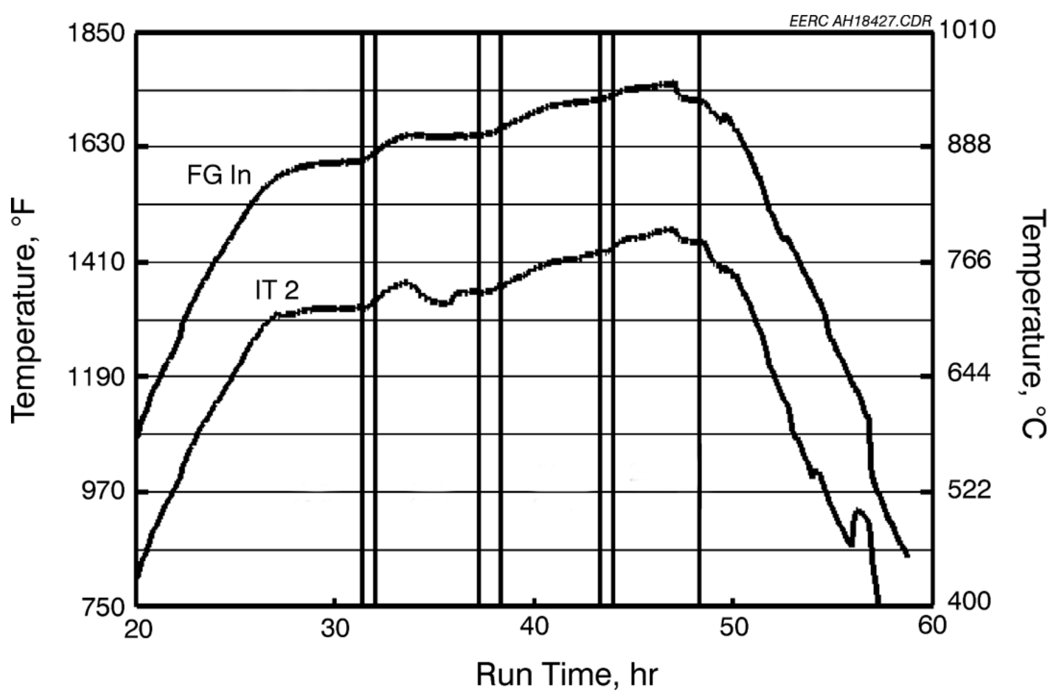

Exhibit 2.2-7
CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the September Test, SFS-RH14-0500

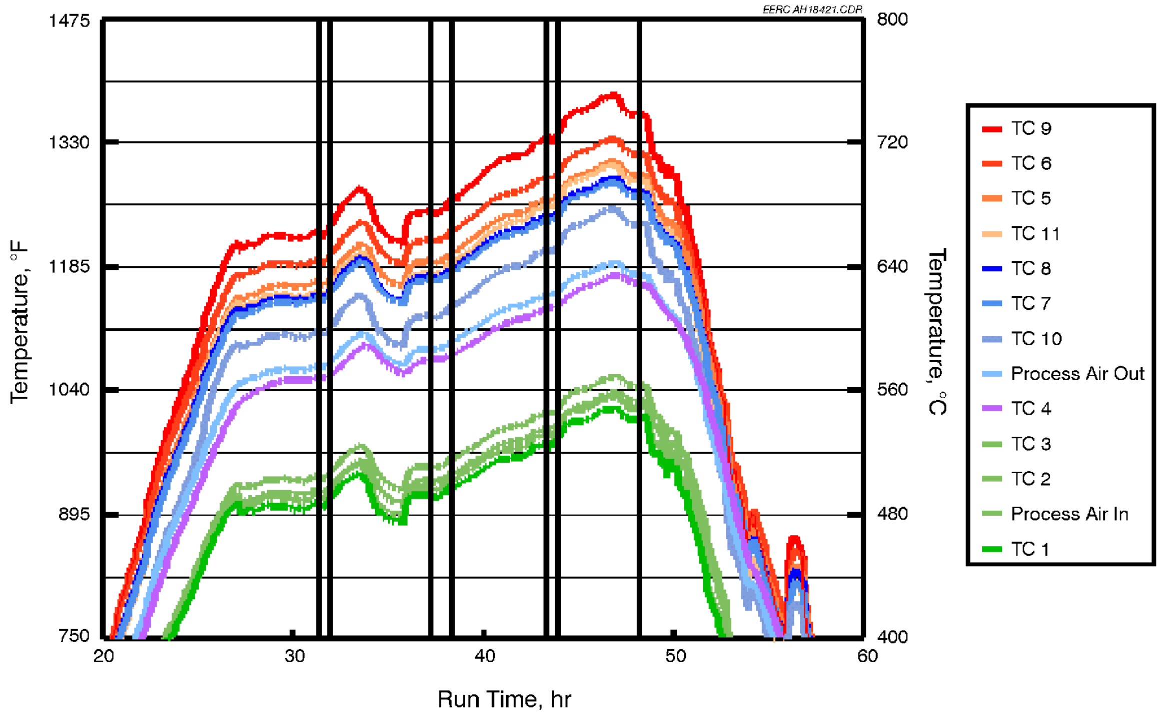

Exhibit 2.2-8
CAH Process Air Temperatures Versus Run Time for the September Test, SFS-RH14-0500

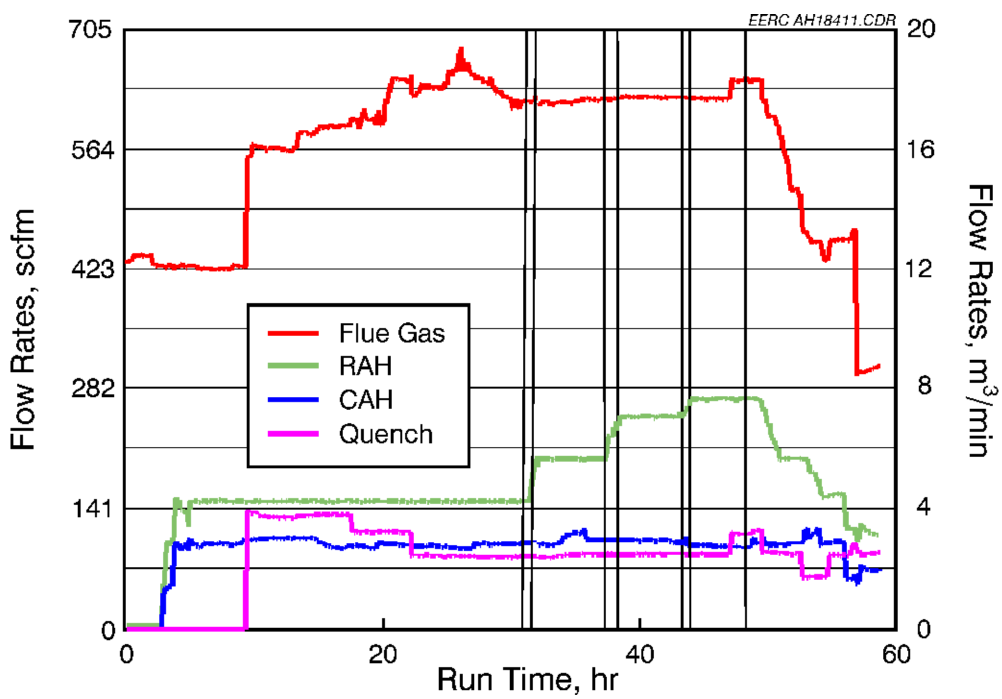

Exhibit 2.2-9
CAH Process Air, RAH Process Air, Quench Gas, and Flue Gas Flow Rates Versus Run Time for the September Test, SFS-RH14-0500

Table 2.2-4
Description of CAH Thermocouple Locations[1]

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

[1] Thermocouple locations are illustrated in Exhibit 2.2-10.

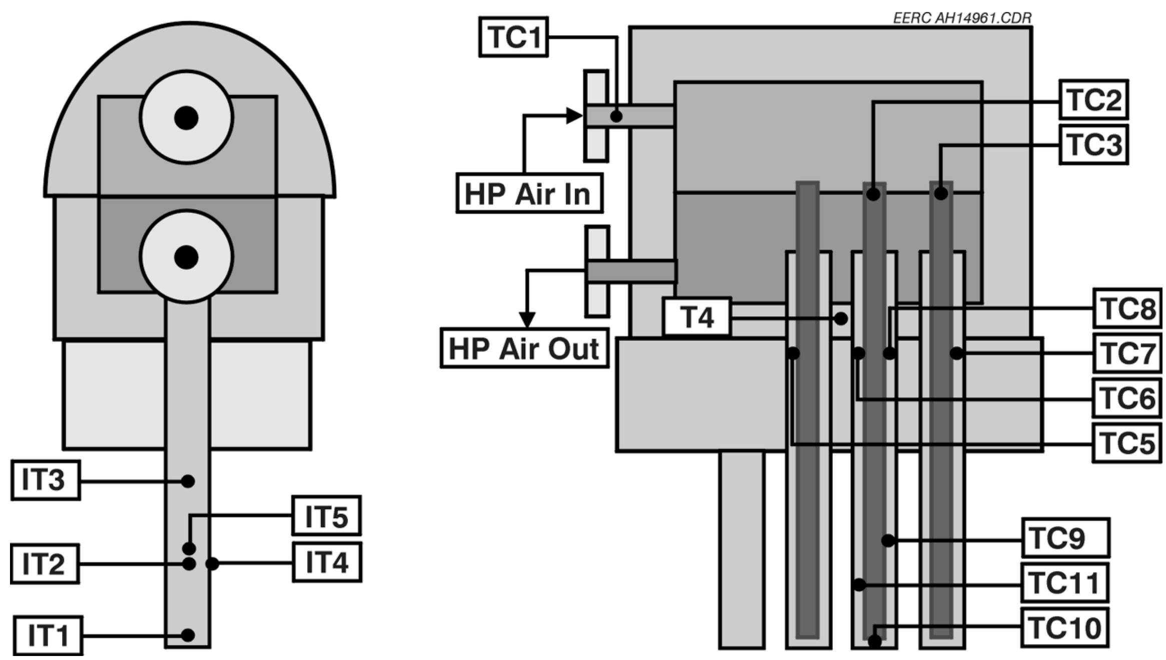

Exhibit 2.2-10
Thermocouple Locations in the CAH Tube Bank

Prior to an August 1998 test, all of the CAH thermocouples were replaced or repaired in conjunction with the installation of fins on the air-cooled tubes. However, one tube surface thermocouple (CAHIT3) was damaged when the tube bank was installed in the flue gas duct. One additional CAH thermocouple failed during both the August and December 1998 tests, and a fourth thermocouple failed at the beginning of a January 1999 test. Therefore, during the September test, only one of the five surface thermocouples was functioning properly. There are no plans to replace these thermocouples at this time because of the time and expense that would be required.

On the basis of a single thermocouple measurement, the clean tube surface temperatures ranged from 1310 to 1470°F (710 to 799°C). Generally, tube surface temperature followed flue gas temperature which followed furnace firing rate. Because natural gas was fired, sootblowing was not necessary during the September SFS test. Process air flow rate adjustments were minimal during the September test, resulting in flow rates of 98-113 scfm (2.8–3.2 m^3/min). Inlet process air temperature ranged from 910 to 1065°F (488 to 574°C), with outlet process air temperatures ranging from 1065 to 1190°F (574 to 643°C). As with tube surface temperature, process air temperature generally followed flue gas temperature as a result of furnace firing rate. However, the changes in process air temperature observed between Run Hours 30 and 40 were the result of a temporary increase and then a subsequent decrease in process air flow rate.

During previous SFS tests while natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank typically ranged from 37,000 to 40,000 Btu/hr (39,000 to 42,200 kJ/hr), depending on process air flow rate and furnace firing rate. In September, heat recovery from the CAH tube bank ranged from 31,580 to 38,470 Btu/hr (33,320 to 40,590 kJ/hr) and was typically <35,000 Btu/hr (<36,925 kJ/hr). The lower level of heat recovery observed in September was directly related to the lower flue gas temperature and flow rate to which the CAH tube bank was exposed as a result of furnace firing rate. Exhibit 2.2-11 presents heat recovery in the CAH as a function of run time. As previously stated with respect to tube surface and process air temperature, the increase and subsequent decrease in CAH heat recovery between Run Hours 30 and 40 were the result of changes made to process air flow rate. Decreasing heat recovery after Run Hour 40 was also due to decreasing process air flow rate until a shutdown of the SFS was initiated at Run Hour 48.

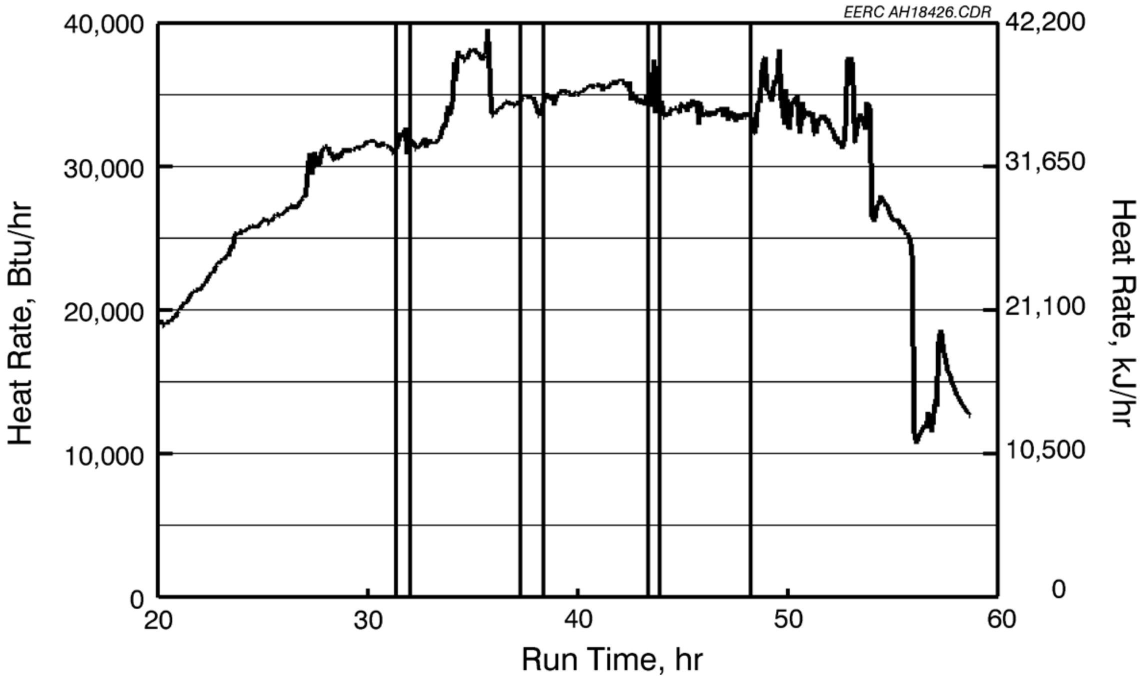

Exhibit 2.2-11
CAH Heat Recovery Versus Run Time for the September Test, SFS-RH14-0500

Testing of the RAH Panel

Initial shakedown and testing of the RAH panel took place in December 1997. Based on RAH tile inspection following the June SFS test, the EERC determined that further testing with the Kyocera tiles installed for the June SFS test was not warranted because of the extensive tile cracking observed as a result of two thermal cycles. In response to discussions with UTRC and Kyocera personnel, the Kyocera tiles were removed from the RAH panel in September and were placed back in their original shipping crates. At this time, there are no specific plans to characterize these tiles.

Testing of the RAH panel within the scope of this project was completed in September 2000 with the completion of a short (3-day) natural gas-fired SFS test. However, data from the September test were not available for inclusion in the July through September quarterly technical progress report. Therefore, the balance of the RAH discussion will focus on data and observations resulting from the SFS test completed in September 2000.

As described previously, the main purpose of the September test (SFS-RH14-0500) was to evaluate the performance of the RAH panel without ceramic tiles to protect the heat-transfer surfaces from furnace conditions. Additional objectives were to identify any system limitations, such as process air capacity, that needed to be addressed so that the RAH could be operated without the ceramic panels while coal is fired. If the RAH can be operated without the ceramic panels, then the cost and impedance to heat transfer caused by the panels can be eliminated. In addition, the size of the RAH and time to commercialization can be substantially reduced.

During the gas-fired test, the furnace and RAH heatup rates were limited to 100°F/hr (56°C/hr). Thermocouples and an optical pyrometer were used to monitor the surface temperature of the MA754 alloy tubes. Alloy surface temperatures were not permitted to exceed 2000°F (1093°C). Furnace firing rates and exit temperature and process air flow rates were controlled to prevent the MA754 alloy surfaces from being overheated. Burner swirl was adjusted to minimize the potential for flame impingement on the alloy surfaces.

Exhibit 2.2-12 is a photograph of the RAH after the tiles were removed and before the September SFS test. The photograph shows the position of the MA754 tubes in the RAH cavity. Low density insulating board was installed behind the tubes and at the top and bottom of the cavity to protect high-temperature fibrous mat insulation from furnace conditions. The low density insulating board also provided further protection to the machined elbows at the top and bottom of each MA754 tube and minimized heat transfer to those surfaces. Other observations concerning the photograph include the presence of the upper and lower Monofrax M half-tiles and some high-density refractory repairs above the RAH panel. The Monofrax M half-tiles were left in place because they were in good condition and to protect insulating material from furnace conditions. High-density refractory repairs above the RAH panel were necessary because of cracks that had developed during the June SFS test.

EERC AH18413.CDR

Exhibit 2.2-12
Photograph of the RAH Panel Prior to the September Test

Exhibit 2.2-13 is a photograph of the RAH after the September SFS test was completed. The only differences noted when compared to Exhibit 2.2-12 is the white color of the new high-density refractory as a result of curing and some sintering (blackening) of the edges of some fibrous insulation below the RAH cavity. There were no observed changes to the surface of the MA754 alloy tubes or the Type K thermocouples used to measure surface temperatures. However, the EERC does not expect the Type K thermocouples to survive even low-temperature furnace conditions for any duration. Therefore, if further testing of the RAH panel occurs without tile protection, it will be necessary to replace the Type K thermocouples with a combination of Type R or S thermocouples and one or more optical pyrometers.

EERC AH18414.CDR

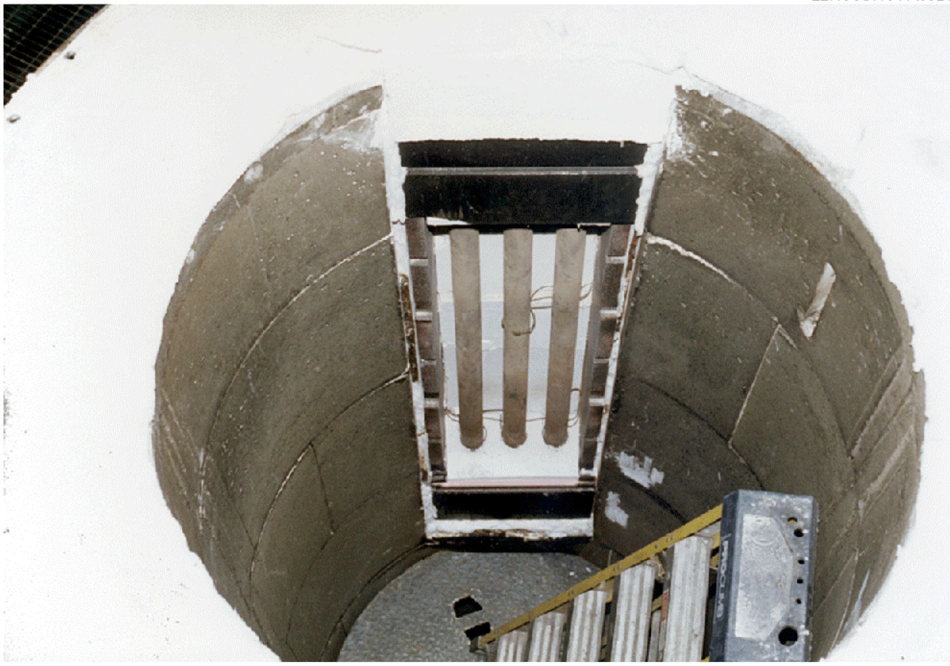

Exhibit 2.2-13
Photograph of the RAH Panel Following the September Test

Exhibits 2.2-14 and 2.2-15 summarize the RAH tube surface temperatures and process air temperatures for the September test (SFS-RH14-0500). The process air flow rate data for the RAH panel were summarized in Exhibit 2.2-9. Exhibit 2.2-16 illustrates the location of thermocouples in the RAH panel, and Table 2.2-5 describes the RAH thermocouples that were used during the September test. Because the ceramic tiles were removed from the RAH panel prior to the September SFS test, there are no tile surface temperature data to discuss.

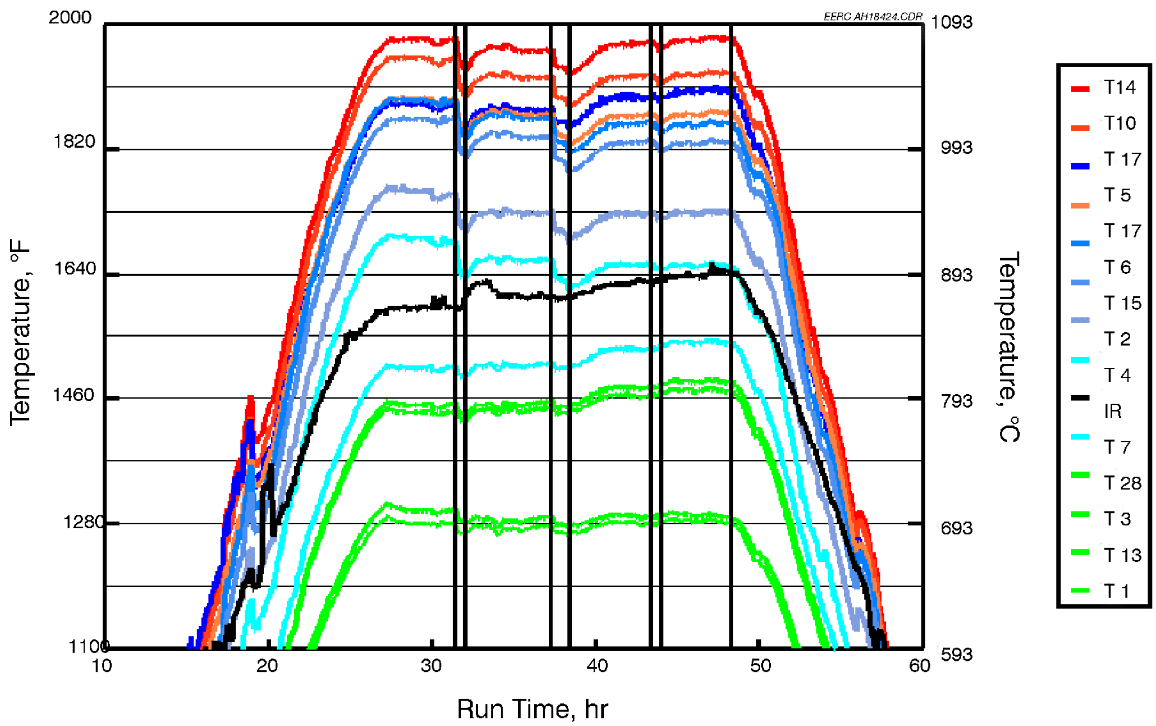

Exhibit 2.2-14
RAH Tube Surface Temperatures Versus Run Time for the September Test, SFS-RH14-0500

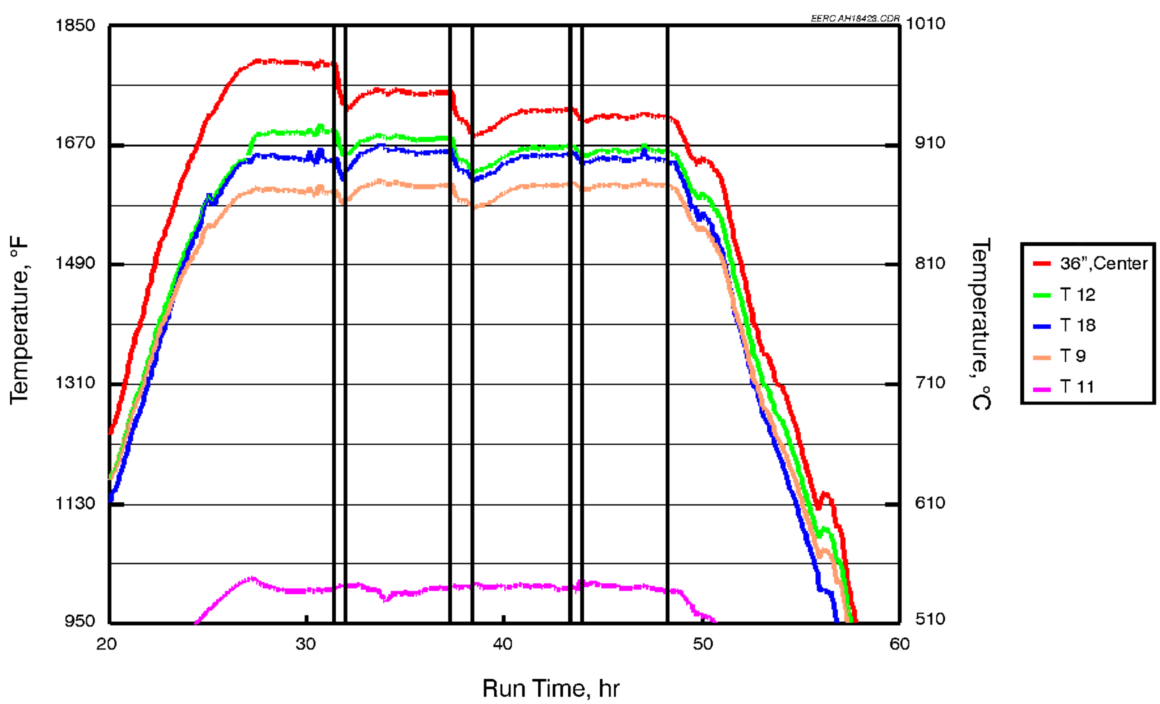

Exhibit 2.2-15
RAH Process Air Temperatures Versus Run Time for the September Test, SFS-RH14-0500

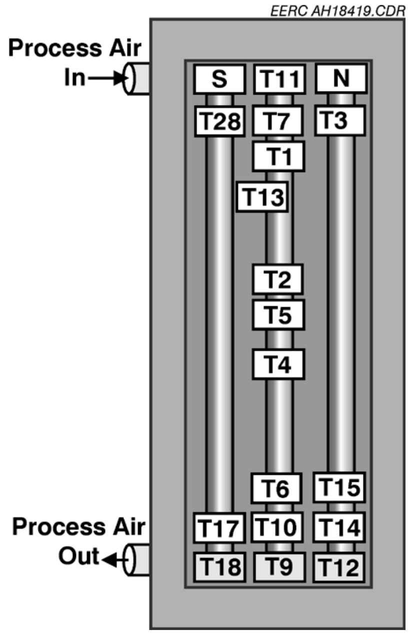

Exhibit 2.2-16
Thermocouple Locations in the RAH Panel

Table 2.2-5
Description of RAH Panel Thermocouple Locations[1]

Category	No.	Label	Description
Air Inlet	1	HP Air In	Provided by the EERC, in pipe before inlet header
	2	RAHT11	Air entering RAH through center tube
Air Outlet	3	RAHT18	Air leaving left (south) tube
	4	RAHT9	Air leaving middle tube
	5	RAHT12	Air leaving right (north) tube
MA Tube Surface	6	RAHT1	Top of center tube facing cold side
	7	RAHT2	Middle of center tube facing other tube
	8	RAHT3	Top of north tube facing toward furnace
	9	RAHT4	Middle of center tube facing cold side
	10	RAHT5	Middle of center tube facing toward furnace
	11	RAHT6	Bottom of center tube facing cold side
	12	RAHT7	Top of center tube facing toward furnace
	13	RAHT8	Removed
	14	RAHT10	Bottom of the center tube facing toward furnace
	15	RAHT13	Top of center tube, facing south tube
	16	RAHT14	Bottom of north tube facing toward furnace
	17	RAHT15	Bottom of north tube facing cold side
	18	RAHT16	Removed
	19	RAHT17	Bottom of south tube facing toward furnace
	20	RAHT28	Top of south tube facing toward furnace
	21	RAHT29	Removed

[1] Thermocouple locations are illustrated in Exhibit 2.2-10

.

RAH process air flow rates during the September test were controlled at 150, 200, 250, and 270 scfm (4.2, 5.7, 7.0, and 7.6 m^3/min). These individual RAH process air flow rates were set, then furnace firing rate was increased until tube surface temperatures approached 2000°F (1094°C). At that point, furnace firing rate was maintained for 4 hr before the process air flow rate was adjusted to the next set point and furnace firing rate increased accordingly. To avoid exceeding the 2000°F (1094°C) temperature limit established for the MA754 tubes, it was necessary in some cases to marginally reduce firing rate during a 4-hr test period as furnace refractory continued to heat. A process air flow rate of 270 scfm (7.6 m^3/min) is currently the maximum flow rate available to support the RAH panel. Additional compressor capacity is available. However, a new process air line will need to be installed to access the available compressor capacity. Installation of a second process air line would permit the use of two existing compressors to support the SFS. In this scenario, a smaller compressor would be used to provide process air to the SFS to meet all air requirements other than the process air required to support the CAH tube bank and RAH panel. The air capacity available for the CAH and RAH would be a minimum of 400 scfm (11.3 m^3/min) and maybe as high as 450 scfm (12.7 m^3/min), depending on compressor performance and line losses. Other modifications to the SFS process air system may be necessary to address other potential limiting factors such as control valve capacity, capacity of flow measurement devices, and process air cooling capacity.

RAH tube surface temperatures ranged from nominally 1270 to 1990°F (688 to 1088°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates had noticeable effects on all tube surface temperatures. Tube surface temperature step changes were most noticeable for surface temperature measurements near the process air outlet and on the front side of the tubes. Tube surface temperatures in September were comparable to those for all previous coal-fired tests near the process air outlets because, for a given process air flow rate, the EERC adjusted furnace firing rate to maintain tube surface temperatures at these locations near limits established for the MA754 alloy. However, the tube temperatures near the process air inlet were generally 100 to 200°F (56 to 111°C) cooler than typically observed when coal was fired. The reason for this difference was the temperature of the process air entering the RAH. RAH inlet process air temperatures during the September test were nominally 1000°F (538°C), roughly 200°F (111°C) lower than inlet process air temperatures observed during coal-fired tests. These lower process air temperatures were the result of reduced heat transfer at the CAH and air preheater tube bundles because of lower flue gas flow rates and temperature, all related to the lower furnace firing rates.

As previously stated, process air inlet temperatures were nominally 1000°F (538°C) during the September SFS test. Outlet process air temperatures ranged from nominally 1600 to 1690°F (871 to 921°C) during the test. The effect of process air flow rate can be seen in the process air outlet temperature data. When process air flow rate was increased, exit temperature decreased. As furnace firing rate was increased to maintain desired tube surface temperatures, the process air exit temperatures returned to nominal values. These flow rate changes are noted at Run Hours 32, 37, and 43.

Heat recovery data from the RAH panel versus run time are presented in Exhibit 2.2-17 for the September test. At process air flow rates of 150, 200, 250, and 270 scfm (4.2, 5.7, 7.0, and 7.6 m^3/min), the heat recovered from the RAH panel was nominally 122,470 Btu/hr (129,210 kJ/hr), 165,310 Btu/hr (174,400 kJ/hr), 201,590 Btu/hr (212,680 kJ/hr), and 218,590 Btu/hr (230,610 kJ/hr), respectively. These nominal values are mean values for individual test periods of 3 to 4 hr. The main burner firing rate ranged from nominally 2.0 to 2.3 MMBtu/hr (2.1 to 2.4×10^6 kJ/hr).

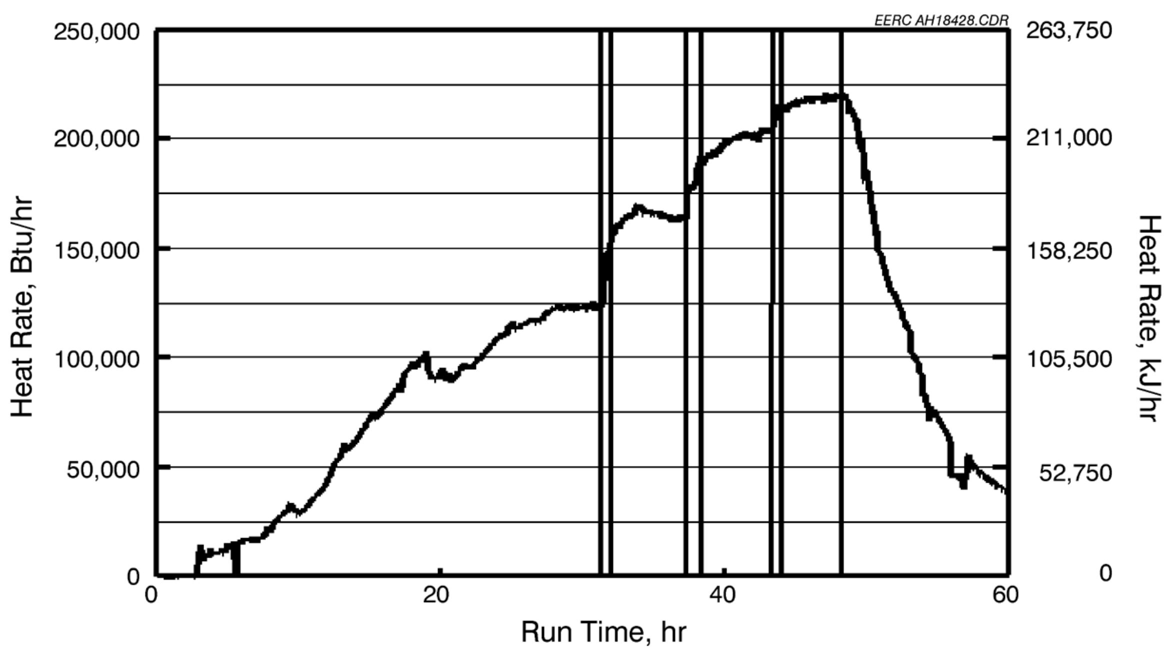

Exhibit 2.2-17
RAH Heat Recovery Versus Run Time for the September Test, SFS-RH14-0500

Exhibit 2.2-18 summarizes RAH heat recovery data at process air flow rates of 180 and 200 scfm (5.1 and 5.7 m^3/min) for bituminous coal-fired tests completed in 1998 through June 2000, the subbituminous coal-fired test completed in March 2000, and the natural gas-fired test completed in September 2000. All of the coal-fired tests utilized ceramic tiles to protect the MA754 alloy tubes from furnace conditions. A comparison of the coal-fired test data with tiles and the September 2000 (RH14) natural gas-fired data without tiles shows that the RAH panel heat recovery in September was 22% to 82% higher for a process air flow rate of 200 scfm (5.7 m^3/min). This is an especially impressive increase in heat recovery given the fact that the coal-fired data with tiles represents furnace temperatures ranging from 2700 to 2950°F (1482 to 1621°C) while the natural gas-fired data without tiles represents a furnace temperature of 2300°F (1260°C).

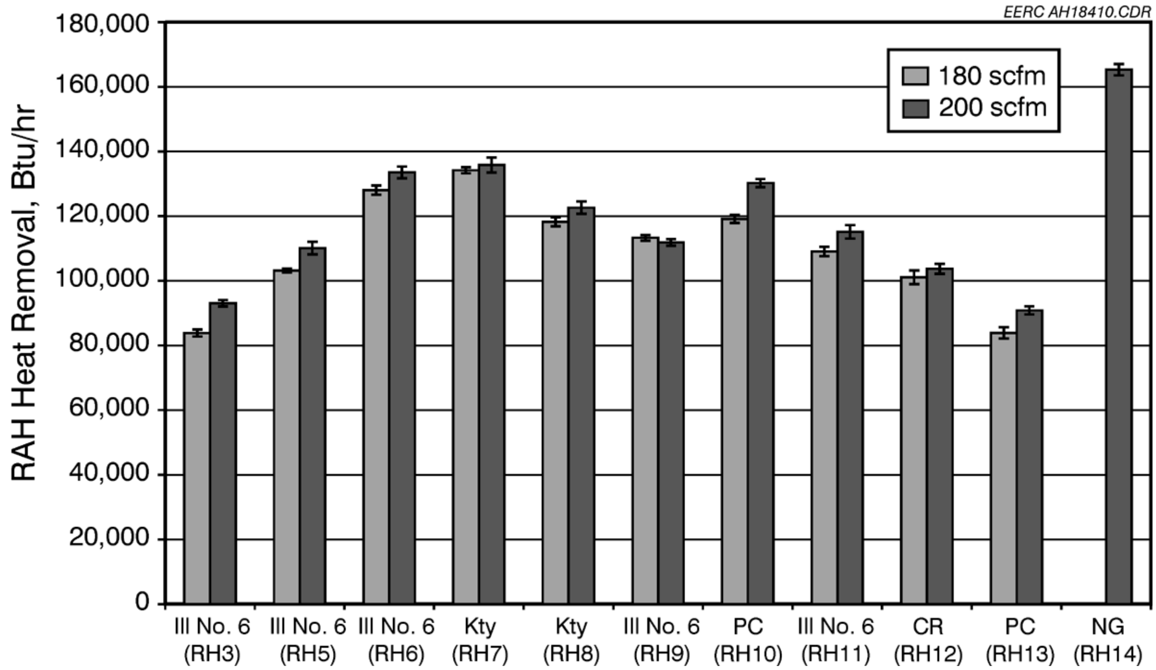

Exhibit 2.2-18
RAH Heat Recovery for Coal-Fired Tests Completed in 1998, 1999, and 2000 and the Natural Gas-Fired Test Completed in September 2000

RAH heat recovery and process air flow rate are plotted versus furnace temperature for the September SFS test in Exhibit 2.2-19. The data generally appear linear for the limited furnace temperature range represented. Whether this indicated trend is real or simply a function of the small data set is uncertain. If additional process air capacity were available to support the RAH panel, this data set could be expanded to document RAH heat recovery without tile protection at higher furnace temperatures. The implication is the potential for significantly higher heat-transfer rates for a given surface area. Assuming success firing natural gas, future coal-fired tests would be warranted to address issues concerning ash and slag deposition on the MA754 alloy surfaces as well as heat transfer.

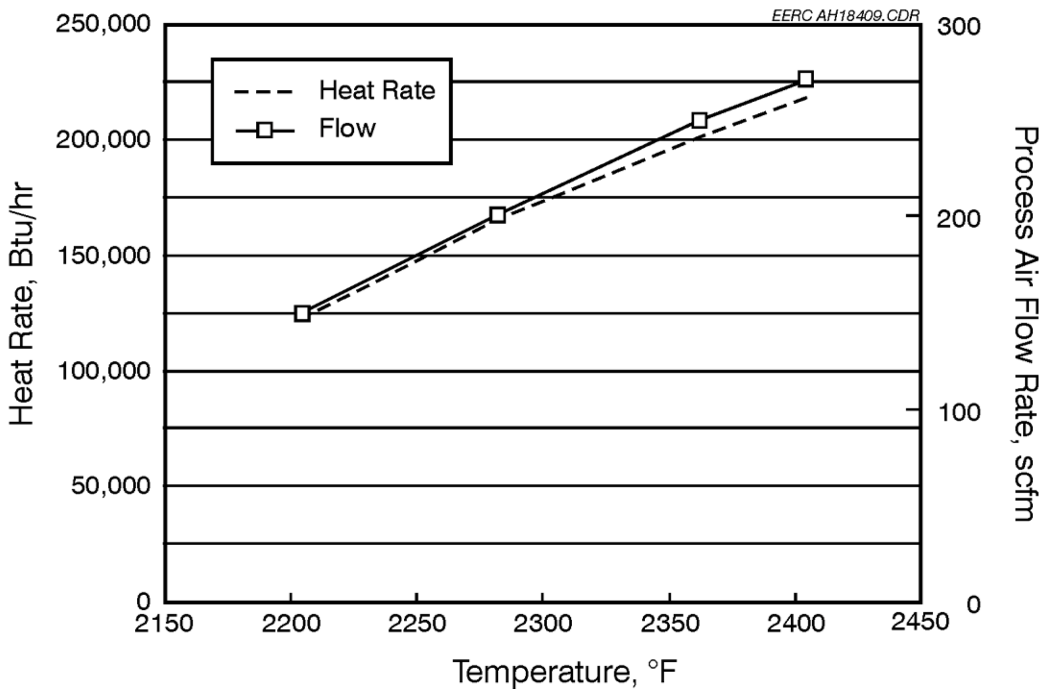

Exhibit 2.2-19
RAH Heat Recovery and Process Air Flow Rate Versus Furnace Temperature for the September Test, SFS-RH14-0500

Table 2.2-6 summarizes operating time for the SFS, CAH tube bank, and RAH panel. Through December 2000, the RAH panel has been exposed to a range of furnace-firing conditions for a total of 2937 hr. Natural gas firing represents 1472 hr (including heatup, cooldown, and refractory curing), and coal/lignite firing represents 1465 hr. In addition, the RAH panel has been exposed to nineteen heating and cooling cycles. The longest continuous coal-fired period was 184 hr, completed in April 1999. The SFS test completed in September is the last planned SFS test within the EERC's subcontract.

Table 2.2-6
Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through December 2000

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	2075	1545	3620
CAH Tube Bank	1760	1512	3272
RAH Panel	1472	1465	2937

Laboratory and Bench-Scale Activities

During this quarter, an attempt was made to perform flowing slag corrosion tests of Plibrico 96 and 98% alumina castable refractories in the dynamic slag application furnace (DSAF) to determine the effectiveness of a coal additive in reducing the corrosivity of coal slag. The test was begun with Illinois No. 6 slag to which 10% alumina fines had been added because tests reported earlier had indicated that with as little as 3% alumina addition to the slag, its corrosivity dropped by a factor of three. However, problems with furnace operation, including a leaking slag injector tube, have prevented the completion of the test in time for this report. Therefore, the results of the test will be reported in the final project report, if the test can be completed in January.

In addition to beginning the DSAF test this quarter, additional viscosity measurements were made on the SFS slag and slag plus additives produced during the March 2000 SFS test of a Powder River Basin coal from the Cordero Rojo mine. The viscosity tests were performed in order to determine what type of coal additives may be effective in reducing the corrosivity of that slag toward the alumina refractories.

Exhibit 2.2-20 shows the variations in the viscosity versus temperature curves for the slag caused by 10% additives of calcium oxide, aluminum oxide, and silicon oxide. The curves show that the Cordero Rojo slag, with and without additives, tends to rapidly solidify at temperatures significantly below the wall temperature in the SFS. A 10% calcium oxide addition both reduces the slag viscosity at high temperatures and the temperature at which it begins to rapidly solidify, the alumina addition has very little effect, and the silica addition increases both viscosity and the temperature at which it begins rapid solidification. However, the silica addition was not sufficient to cause solidification on the walls of the SFS or even within the inner refractory layer. Solidification is important because it would make the slag less corrosive to the refractory. Therefore, the data suggest that although silica additions may help in reducing the slag corrosivity, more than 10% will need to be employed. Heated-stage x-ray diffraction analyses of the slags are continuing in order to help determine how much additive may be necessary.

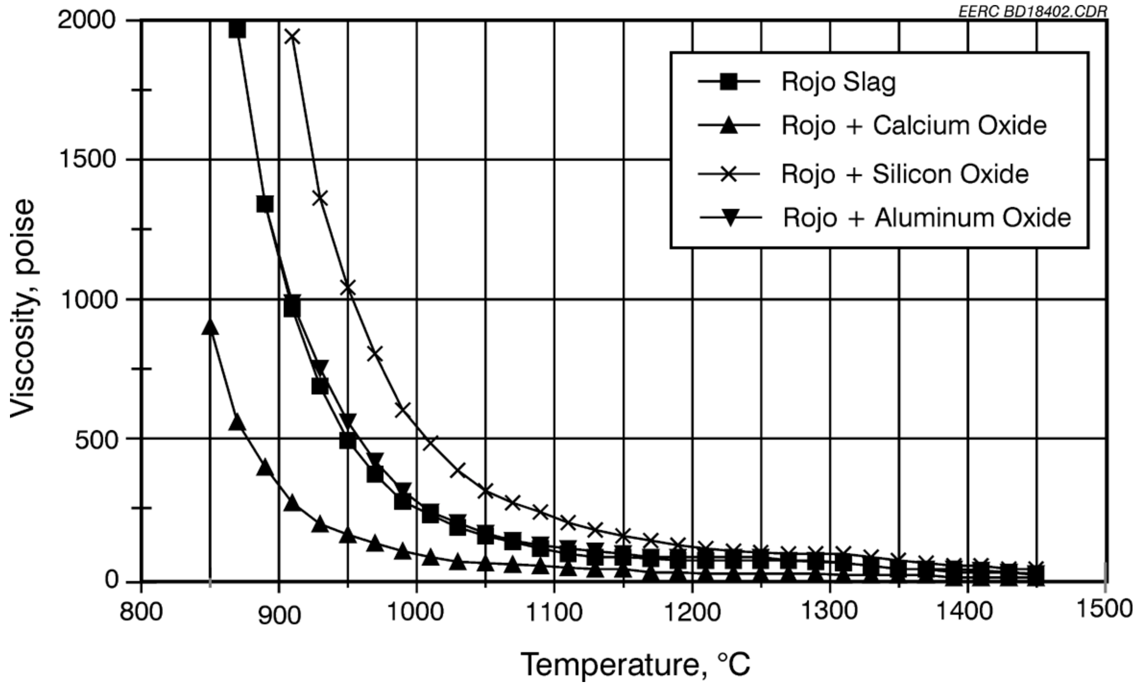

Exhibit 2.2-20
Slag Viscosity Versus Temperature Curves for the Cordero Rojo Slag and Slag Plus 10% Additives of Calcium Oxide, Aluminum Oxide, and Silicon Oxide