Increasing heat exchanger efficiencies and material lifetimes demonstrates to coal-burning utilities that coal-fired options exist and it may not be necessary to switch to natural gas firing or purchase CO_2 credits if CO_2 emission restrictions are legislated. Instead, existing coal-burning boilers can be repowered with an indirectly fired turbine combined cycle to increase efficiency by up to 50% and reduce CO_2 emissions by as much as 40%.

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

2.0 EXPERIMENTAL APPROACH

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

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

2.1 Scope of Work

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

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

Specific test parameters were chosen based on the results of previous tests. Two of the nearly 4 weeks of SFS operation involved firing a low-iron eastern Kentucky bituminous coal to determine if slag tapping presented special problems with such a coal as well as its slag corrosion characteristics relative to the ceramic tiles on the RAH panel. Other test parameters included operating the RAH panel at higher (>1700°F/>927°C) process air outlet temperatures, the use of noncoated refractory brick tiles on the surface of the RAH to determine the effect of high-emissivity coatings on heat exchanger efficiency, and the use of coal additives to mitigate slag flow problems and/or reduce molten slag corrosion of the castable and brick refractories.

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

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

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

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

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

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

Flue gas composition (sulfur dioxide, nitrogen species, CO_2, carbon monoxide, oxygen, and particulate) was measured and is reported. Gas-phase constituents were monitored continuously using on-line instrumentation at the exit of the furnace and pulse-jet baghouse. Sulfur dioxide and nitrogen species data are reported on a lb/MMBtu and concentration basis. Particulate sampling was completed at the inlet and outlet of the baghouse during each week of SFS operation. Sampling at the inlet of the baghouse documented mass loading and particle-size distribution. Sampling at the outlet of the baghouse documented mass and fine particulate emissions. Particulate emissions are reported on a lb/MMBtu and mass per unit volume basis.

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

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

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

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

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

2.2 Description of Pilot-Scale SFS

The EERC pilot-scale SFS is designed to simulate the conditions in the commercial-scale UTRC HITAF (high-temperature advanced furnace) concept. The SFS is pictured in Figure 2-1, with a schematic of the system shown in Figure 2-2. The SFS is designed for a maximum furnace exit temperature of 2900°F (1593°C), but is typically run at 2750°F (1510°C) at the exit in order to maintain the desired slag flow while extending the furnace lifetime. It has a nominal firing rate of 2.5 MMBtu/hr (2.6×10^6 kJ/hr) and a range of 2.0 to 3.0 MMBtu/hr (2.1 to 3.1×10^6 kJ/hr) using a single burner. The design is based on a bituminous coal (Illinois No. 6) and a nominal furnace residence time of 3.5 s. Resulting flue gas flow rates range from approximately 425 to 640 scfm (12 to 18 m^3/min), with a nominal value of 530 scfm (15 m^3/min) based on 20% excess air. Firing subbituminous coal or lignite increases the flue gas volume, decreasing residence time to as low as 2.7 s. However, the high volatility of subbituminous coal or lignite results in high combustion efficiency (>99%). The EERC oriented the furnace vertically (downfired) and based the burner design on a swirl burner successfully used on two smaller EERC pilot-scale pc-fired units (0.6 MMBtu/hr [0.7×10^6 kJ/hr]). The furnace dimensions are 47 in. (119 cm) inside diameter (i.d.) by roughly 16 ft (4.9 m) in total length. It is lined with three layers of refractory totaling 12 in. (30.5 cm) thick. The inner layer is composed of an alumina castable, developed by the EERC in cooperation with the Plibrico Company, that has been shown in laboratory tests to be extremely resistant to slag corrosion relative to other commercially available castable refractories.

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

EERC GW16581.CDR

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

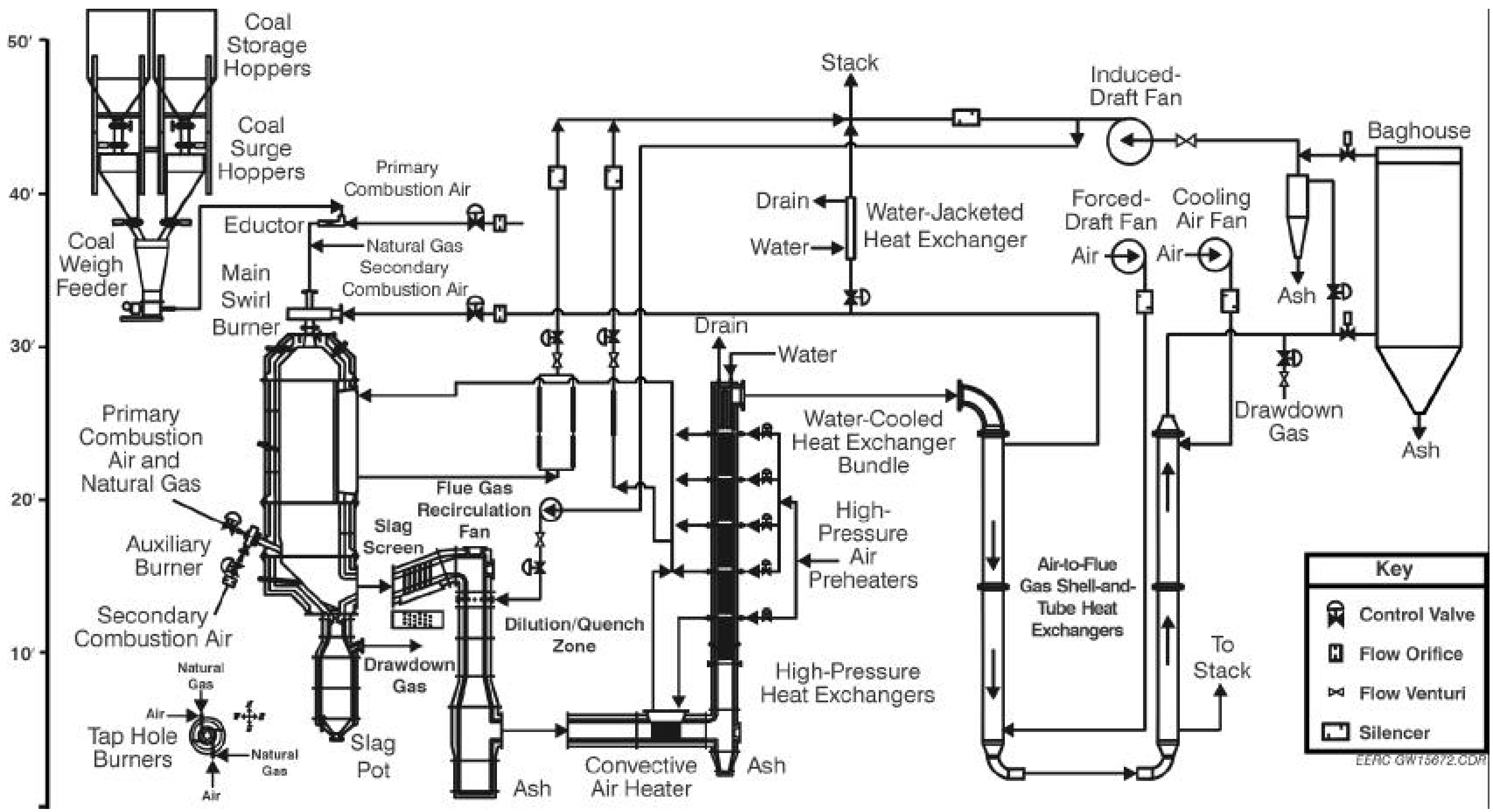

Figure 2-2. Combustion 2000 slagging furnace and support systems.

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

As the hot gases leave the combustion zone, they pass through a slag screen, which is designed to remove the entrained ash as a nonleachable slag and reduce deposition on the CAH tubes. Tests with the slag screen showed that its performance is fuel-dependent and that when firing Illinois No. 6 coal it removes approximately 65% of the particulate matter from the gas stream. As the hot combustion gas leaves the slag screen, it is quenched with recirculated flue gas to 1850°F (1010°C) in order to reduce the stickiness of the ash to minimize deposition on the CAH tubes. The quench zone is the only region in the furnace where hard slag/ash deposits form, but they are easily removed by knocking them into a hopper at the bottom of the zone. The gases then pass through the CAH tube bank which is used to heat process air from 1000° up to 1300°F (538° to 705°C) to support operation of the RAH. The hot combustion gases flow from the CAH tube bank through a series of heat exchangers and, finally, a baghouse on the way to the system stack.

2.2.1 Fuel Feed System

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

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

Specifications for the weigh feeder included the following:

- Pulverized fuel density (40 lb/ft^3 or 641 kg/m^3)
- Particle size (70% <0.0030 in. or 75 µm; 300-µm top size)
- Feed rate range (200–500 lb/hr or 91–227 kg/hr)
- Minimum hopper capacity (10 ft^3 or 0.3 m^3)
- Nonpulsing feed (twin screw)
- Gravimetric (loss-in-weight) and volumetric feed modes
- Minimum 20-bit resolution load cell (high-resolution digital)
- User-programmable microprocessor control

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

The main burner is natural gas- and pulverized fuel-capable. The basic design is an International Flame Research Foundation (IFRF)-type adjustable secondary air swirl generator which uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl. Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NO_x. Carbon efficiency has been >99% in the slagging furnace for all fuels fired to date. High carbon efficiencies can be obtained in the slagging furnace at relatively low swirl settings because of the high operating temperature. Combustion air flow rates through the main burner range from about 400 to 600 scfm (11 to 17 m^3/min), depending on furnace firing rate and the fuel type (bituminous, subbituminous, or lignite) fired.

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

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

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

2.2.2 Slagging Furnace

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

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

TABLE 2-1

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

Furnace Firing Rate, kBtu/hr:	2000	2500	3000
Furnace			
Furnace i.d., in.	47	47	47
Furnace Length, ft	16	16	16
Refract. 1 Thickness, in.	4	4	4
Refract. 2 Thickness, in.	4	4	4
Refract. 3 Thickness, in.	3.25	3.25	3.25
Furnace Weight, tons	14.4	14.4	14.4
Inlet Gas Temp., °F	2900	3000	3100
Avg. Gas Temp., °F	2800	2850	2900
Exit Gas Temp., °F	2700	2700	2700
Refract. 1 Surf. Temp., °F	2677	2728	2777
Refract. 2 Surf. Temp., °F	2431	2477	2521
Refract. 3 Surf. Temp., °F	1751	1783	1815
Furnace Skin Temp., °F	275	279	283
Coal Feed Rate, lb/hr	176	220	264
Airflow Rate, scfm	398	497	597
Flue Gas Flow Rate, scfm	428	536	643
Flue Gas Flow Rate, acfm	2683	3412	4155
Furnace Gas Velocity, ft/s	3.7	4.7	5.7
Flue Gas Residence Time, s	4.1	3.2	2.6
Auxiliary Burner Air, scfm	164	110	20
Auxiliary Burner, kBtu/hr	890	560	110
Total Firing Rate, kBtu/hr	2890	3060	3110
Wall Losses, kBtu/hr	194	202	209
RAH Losses, kBtu/hr	190	190	190

	2000	2500	3000
Furnace Exit/Slag Screen			
Total Flue Gas Flow, scfm	592	646	663
Total Flue Gas Flow, acfm	3598	3926	4029
Furnace Exit Vel., ft/s	33.2	36.2	37.2
Slag Screen Exit Gas Vel., ft/s	66.4	72.5	74.4
Dilution Gas Requirements			
Inlet Flue Gas Temp., °F	2520	2535	2540
Gas Velocity In, ft/s	61.3	67.3	69.2
Exit Gas Temp., °F	1855	1851	1850
Dilution Gas Temp., °F	300	300	300
Dilution Gas Flow, scfm	248	280	289
Total Flue Gas Flow, scfm	840	926	952
Flue Gas Flow Rate out, acfm	3740	4115	4229
Gas Velocity out, ft/s	67.6	74.4	76.5
Dilution Gas Nozzles			
Nozzle Diameter, in.	1.25	1.25	1.25
No. of Nozzles	8	8	8
Dilution Gas Flow, acfm	362	409	422
Dilution Gas Velocity, ft/s	89	100	103
Convective Air Heater			
Gas Temp., °F	1800	1800	1800
Flue Gas Flow Rate, acfm	3651	4025	4138
Gas Velocity, ft/s	52.2	57.5	59.1

Assumption: Excess air is 20%.

The refractory walls in the slagging furnace consist of three castable refractory layers with a total thickness of 11.25 in. (28.58 cm). The three layers include 4 in. (10.2 cm) of high-density (14 Btu-in./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 3.25 in. (8.3 cm) 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 reduce the overall size and weight of the system. Because of its greater structural strength and high corrosion resistance, Plibrico Plicast Cement-Free 98V KK alumina castable was originally used in the top three furnace sections, in the exit of the furnace, and in the top section of the dilution/quench zone. The Plicast Cement-Free 98V KK is an alumina castable, developed by the EERC in cooperation with the Plibrico Company, that has been shown in laboratory tests to be extremely resistant to slag corrosion. Plicast Cement-Free 99V KK was used in the bottom furnace section (except for the exit) because of its even greater potential resistance to slag attack. Repairs to the high-density refractory in the top section of the furnace and the upper-middle furnace section are required on a periodic basis.

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

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

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

TABLE 2-2

Refractory Properties

Refractory:	Plicast Cement-Free 99V KK/99V[1]	Plicast Cement-Free 98V KK/98V[1]	Plicast Cement-Free 96V KK/96V[1]	Narco Cast 60	Plicast LWI-28	Plicast LWI-20	Harbison-Walker 26
Function	High density	High density	High density	High density	Insulating	Insulating	Insulating
Service Limit, °F	3400	3400	3300	3100	2800	2000	2600
Density, lb/ft^3	185	185	185	145	80	55	66
K, Btu-in./ft^2 °F-hr @ 2000°F	14.5	14.5	14.0	6.5	4.0	NA[2]	2.2
K, Btu-in./ft^2 °F-hr @ 1500°F	14.7	14.7	14.2	6.0	3.0	1.7	1.9
K, Btu-in./ft^2 °F-hr @ 1000°F	15.5	15.5	15.0	5.6	2.7	1.3	1.7
Hot MOR[3] @ 2500°F, psi	650	750	1400	NA	NA	NA	NA
Hot MOR @ 1500°F, psi	–	–	2000	1000	250	100	110
Cold Crush Strength @ 1500°F, psi	–	–	10000	NA	750	400	350
Typical Chemical Analysis, wt% (calcined)							
Al_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.

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

2.2.3 Radiant Air Heater Panels

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

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

Furnace design also permits the installation of a smaller sized 1.5- × 5.4-ft (0.46- × 1.65-m) SRAH panel. The purpose of the SRAH panel was to expose ceramic materials to slagging furnace conditions to evaluate their slag corrosion properties rather than generating heat-transfer data. The SRAH was constructed with a variety of refractory plates and was designed only for testing material lifetimes. A primary difference between the LRAH and SRAH panels was that the SRAH panel was cooled with water rather than heated air. The SRAH panel was water-cooled using two sets of five vertically oriented 0.375-in. (0.952-cm) outside diameter (o.d.) stainless steel tubes. While the SRAH panel was 1 ft (0.3 m) shorter than the LRAH panel, both assemblies were the same width and use the same air-cooled frame support design. A central vertical ceramic rail was present in the SRAH panel, allowing the installation of either full-width (18-in./46-cm) or half-width panels inside the furnace. The SRAH panel ceramic tiles were damaged in August 1998. Based on technical and economic considerations, the SRAH panel was not rebuilt. Therefore, the SRAH panel was not available for use in support of this project.

2.2.4 Slag Screen

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

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

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

The walls of the slag screen consist of two refractory layers. The inner, high-density layer is a Plicast Cement-Free 98V KK with an outer insulating layer of Harbison-Walker Castable 26. The high-density refractory is 2.25 in. (5.7 cm) thick in the sidewalls and 4 in. (10.2 cm) thick in the roof and floor of the slag screen. The insulating refractory is 3.75 in. (9.5 cm) thick in the sidewalls, roof, and floor. A Plicast LWI-28 refractory was used around the sight ports in the wall of the slag screen. Properties for the high-density and insulating refractories selected for use in the slag screen are summarized in Table 2-2.

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

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

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

2.2.5 Dilution/Quench Zone

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

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

2.2.6 Convective Air Heater

The CAH design was a cooperative effort between the EERC and UTRC. It was constructed by UTRC and assembled and installed in September 1997. The flue gas flow rate to the CAH tube bank has been calculated by the EERC to range from 3553 to 4619 acfm at 1800°F (101 to 131 m^3/min at 982°C) depending on the firing rate and fuel fired in the SFS. 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 tube bank. Heat is recovered from the flue gas to meet process air temperature requirements for the CAH. The design process air exit temperature from the CAH is 1200°F (649°C) and is not permitted to exceed 1300°F (705°C). Process air flow rate is used to control process air exit temperature using a flow control valve.

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

Prior to the August 1998 test, fins were added to the air-cooled tubes in the CAH to improve heat transfer. The fins are 1-in. (2.5-cm) by 0.125-in. (0.318-cm) flat material and run the length of each tube on both the leading and trailing edges of the tube surface. Based on the August 1998 and subsequent data, it appears that the addition of the fins improved heat recovery during coal-fired test periods. The fins appear to have reduced the rate of heat-transfer degradation as ash deposits developed and helped to maintain a higher heat-transfer rate once the deposits had formed. However, no improvement in heat recovery was observed during natural gas-fired periods with clean tube surfaces.

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

2.2.7 Process Air Preheaters

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

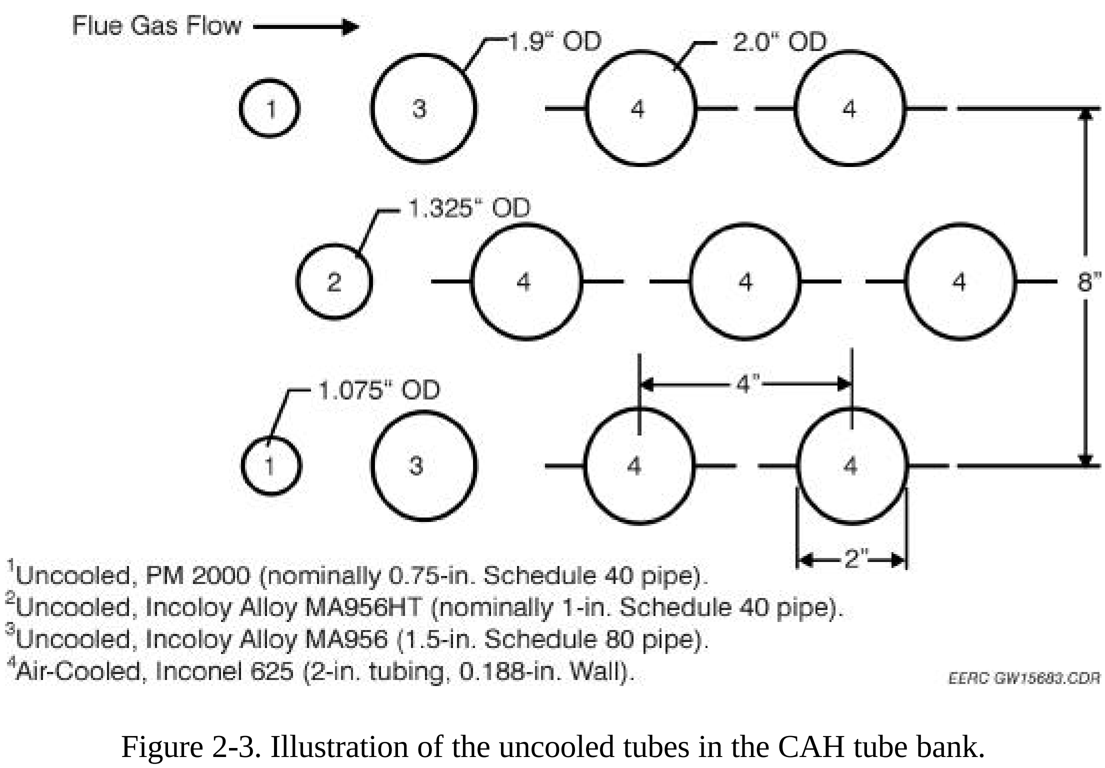

Figure 2-3. Illustration of the uncooled tubes in the CAH tube bank.

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

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

Operational performance of the process air preheater tube bundles, piping subsystem, and process control scheme has been very good. Because of higher flue gas flow rates during natural gas firing, the air temperature exiting the process air preheater tube banks is higher when compared to coal-fired periods at comparable process air flow rates. However, during coal firing, it is still possible to obtain exit temperatures of 1300°F (705°C) at process air flow rates of 200 scfm (5.7 m^3/min), even though the heat-transfer rate degrades with ash deposition on the tube surfaces. Further heating of the process air entering the RAH panel is achieved electrically and by recovering heat from the CAH tube bank. In addition, air compressor system and power failures have been encountered resulting in the use of the nitrogen backup system. The nitrogen backup system has functioned as intended during these support system failures, supplying an emergency cooling media to the process air preheaters and ultimately supporting the CAH tube bank and RAH panel.

2.2.8 Slagging Furnace System Heat Exchangers

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

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

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

2.2.9 System Fans

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

TABLE 2-3

Pressure, Temperature, and Flow Specifications for the SFS Fans

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

2.2.10 Emission Control

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

Flue gas flow rates to the baghouse can range from a low of 630 scfm (17.8 m^3/min) at 350°F (177°C), to a maximum of 1063 scfm (30.1 m^3/min) at 700°F (371°C). Therefore, the baghouse design was based on an average flue gas flow rate of 850 scfm (24.1 m^3/min) at 350°F (177°C) or 1900 acfm (53.8 m^3/min) at 700°F (371°C), based on a nominal furnace firing rate of 2.5 MMBtu/hr (2.6×10^6 kJ/hr). The baghouse is sized to accommodate a maximum of 36 bags mounted on wire cages with 2-in. (5-cm) bag spacing. Bag dimensions are nominally 6 in. (15.2 cm) in diameter by 10 ft (3.0 m) in length, providing a total filtration area of 565 ft^2 (52.5 m^2).

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

To date, only one tube sheet has been constructed, permitting the installation of 36 bags arranged in a six-by-six array. Installing the maximum number of bags permits the SFS to be operated over the broadest potential range of conditions while minimizing the potential impact of the baghouse on overall system performance. Each filter bag is secured to the tube sheet using a snap band sewn into the top cuff. Stainless steel (304 SS) wire cages with 20 vertical wires and 6-in. (15-cm) ring spacing provide bag support. The pulse-jet baghouse is a single compartment capable of either on- or off-line cleaning. Flue gas enters the baghouse in an area just below the bottom of the cage-supported bags and above the ash hopper. Access to the filter bags and stainless steel wire cages is gained by removing the clean air plenum at the top of the baghouse. The fabric type used during tests documented in this report was a 22-oz/yd^2 (744-g/m^2) woven glass bag with a polytetrafluoroethylene (PTFE) membrane. Prior to the tests documented in this report, a 16-oz/yd^2 (543-g/m^2) Huyck felt material was used. Baghouse performance observations as a result of this project are summarized later in this report.

The SFS does not have a sulfur dioxide control system, and there are no plans to install one at this time. Dispersion modeling data developed by the North Dakota State Health Department indicates that the stack height, flue gas velocity at the stack exit, and dilution effect of the system process air that is exhausted through the stack permits a maximum sulfur dioxide emission rate of 20.8 lb/hr (9.4 kg/hr). The SFS sulfur dioxide emission rate is limited to 20.8 lb/hr (9.4 kg/hr) to avoid the potential to exceed the 1-hour ambient air quality standard of 715 µg/m^3. However, based on operating experience with bituminous and subbituminous coal and lignite, the EERC has never exceeded a sulfur dioxide emission rate of 18 lb/hr (8.2 kg/hr).

2.2.11 Instrumentation and Data Acquisition

The instrumentation and data acquisition components for the pilot-scale SFS address combustion air, flue gas, process air, process water, temperatures, static and differential pressures, and flow rates. The data acquisition system is based on a Genesis software package and three personal computers. Two sets of flue gas instrumentation (oxygen, CO_2, carbon monoxide, sulfur dioxide, and nitrogen species) are dedicated to support the operation of the SFS. Flue gas is transferred from the sample point through a heated filter and sample line to the sample conditioner before it reaches the analyzers. Flue gas is routinely sampled in the slag screen at the furnace exit and the exit of the baghouse. Total flue gas flow rate through the SFS is measured using a venturi.

2.3 Dynamic Slag Application Furnace

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

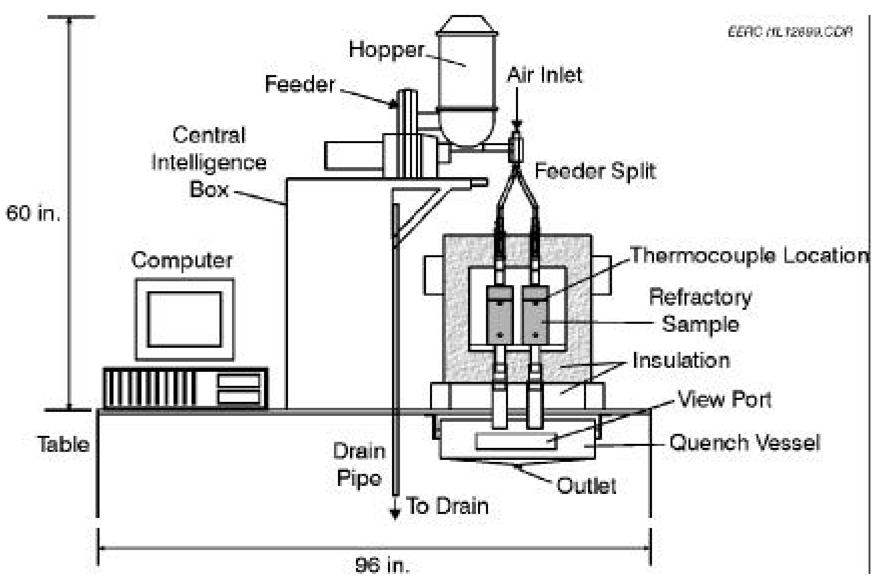

Figure 2-4. Schematic of the DSAF.