

3.0 RESULTS AND DISCUSSION

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

3.1 Pilot-Scale Testing

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

3.1.1 Pilot-Scale SFS Performance

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

Fuel Characteristics

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

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

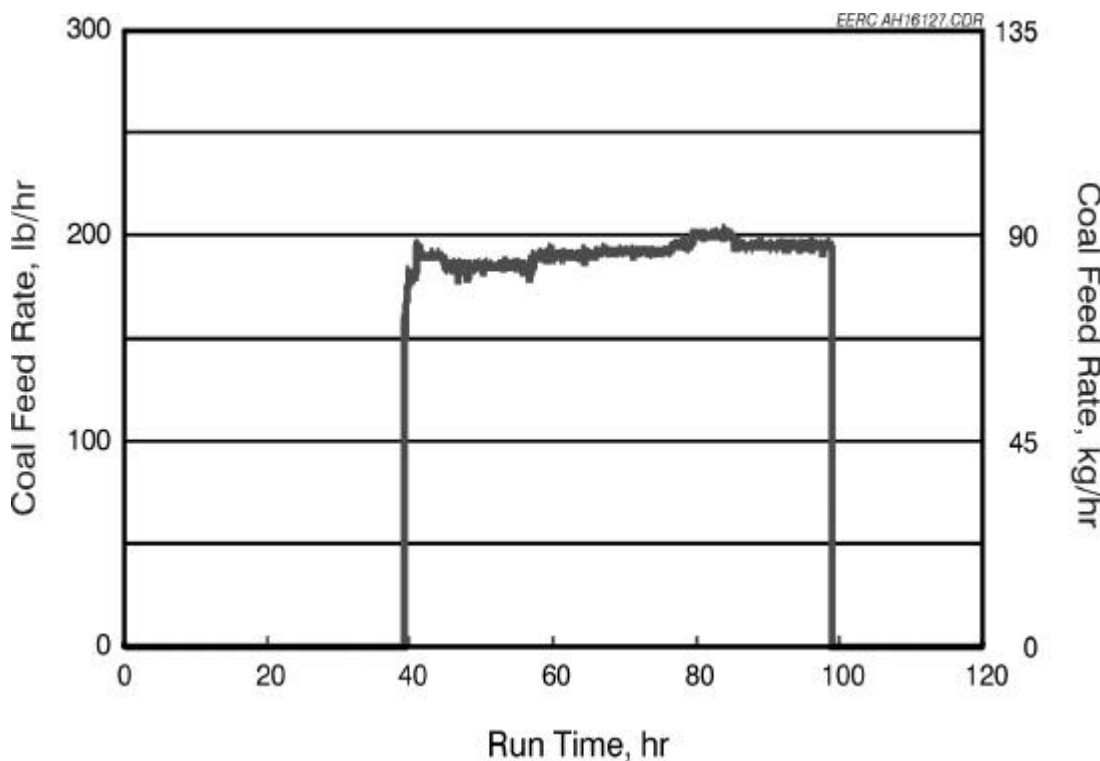


Figure 3-1. Coal feed rate versus run time for the January 1999 test, SFS-RH6-0199.

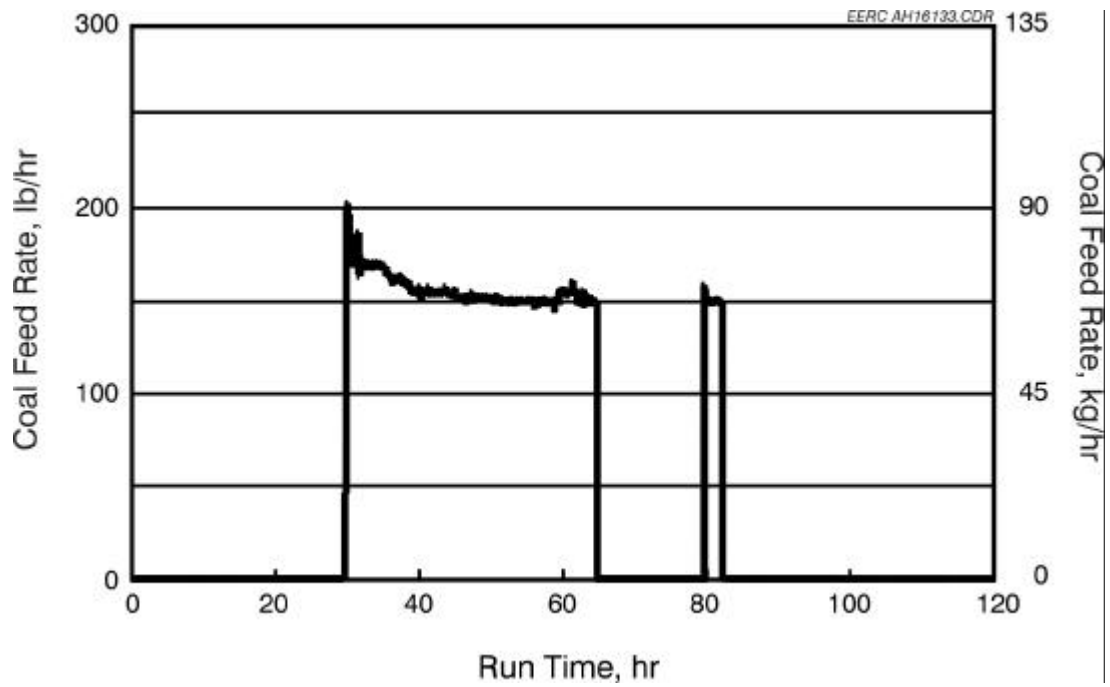


Figure 3-2. Coal feed rate versus run time for the February 1999 test, SFS-RH7-0299.

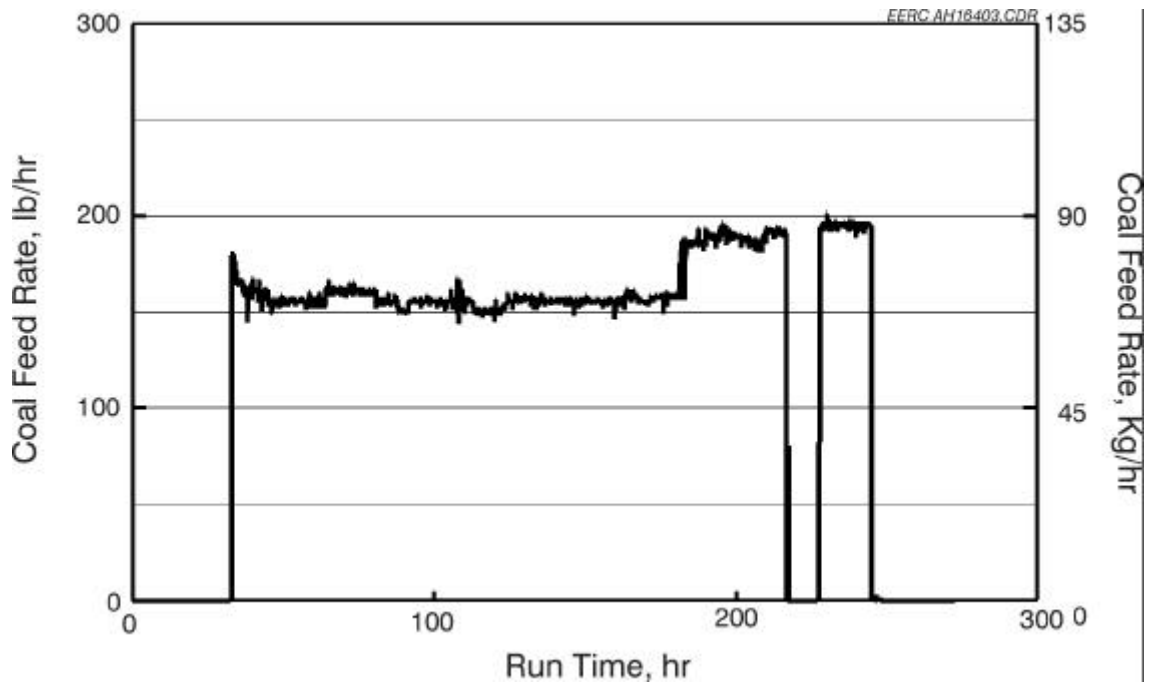


Figure 3-3. Coal feed rate versus run time for the April 1999 test, SFS-RH8-0399.

TABLE 3-1

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

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

TABLE 3-2

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

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

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

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

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

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

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

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

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

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

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

Slagging Furnace Operation

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

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

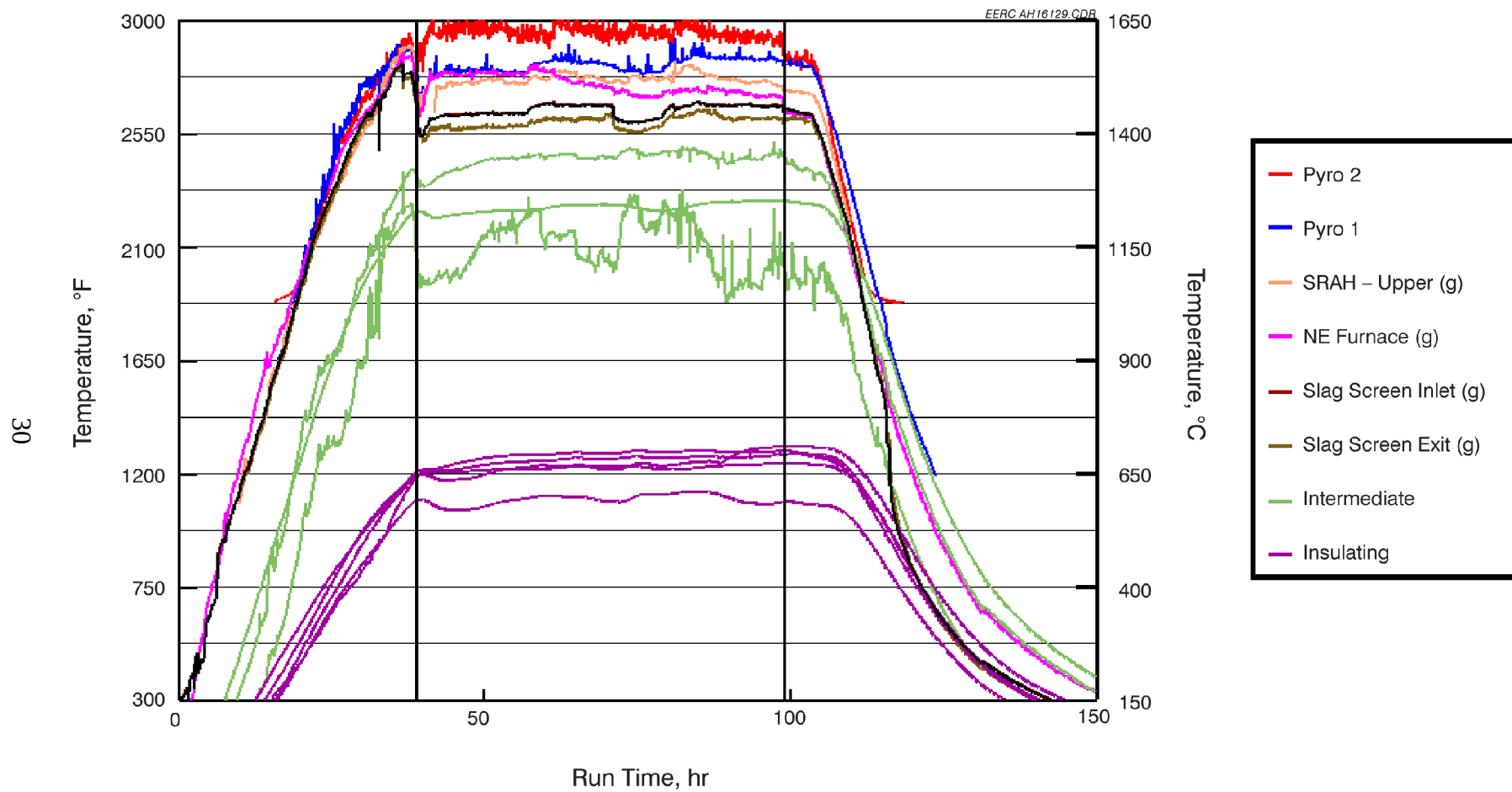


Figure 3-4. Furnace and slag screen temperatures versus run time for the January 1999 test, SFS-RH6-0199.

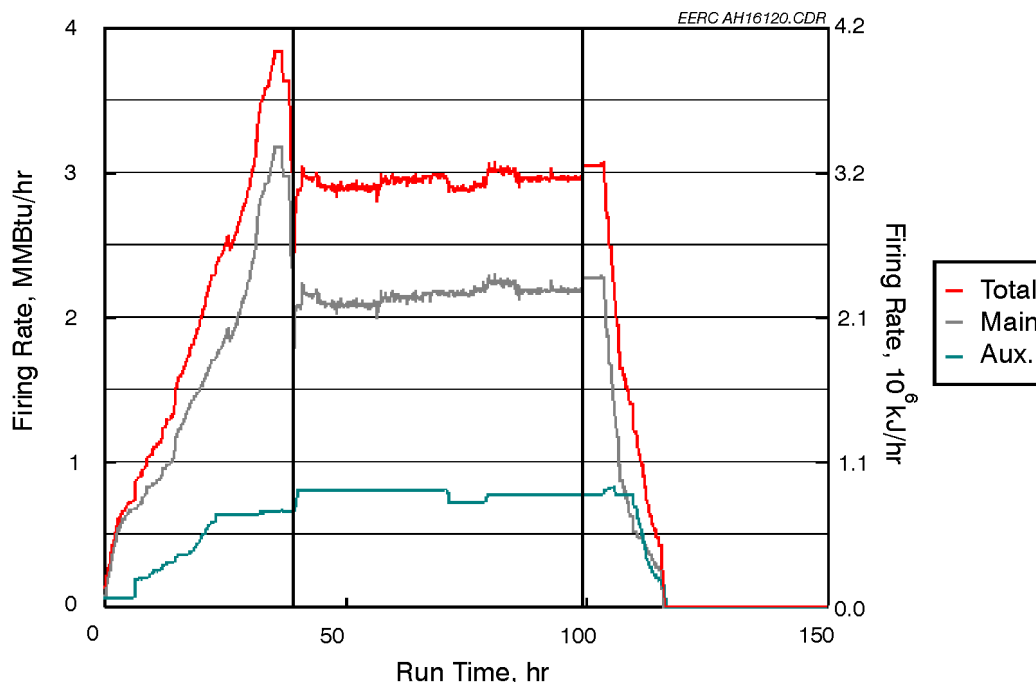


Figure 3-5. Slagging furnace firing rate versus run time for the January 1999 test, SFS-RH6-0199.

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

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

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

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

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

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

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

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

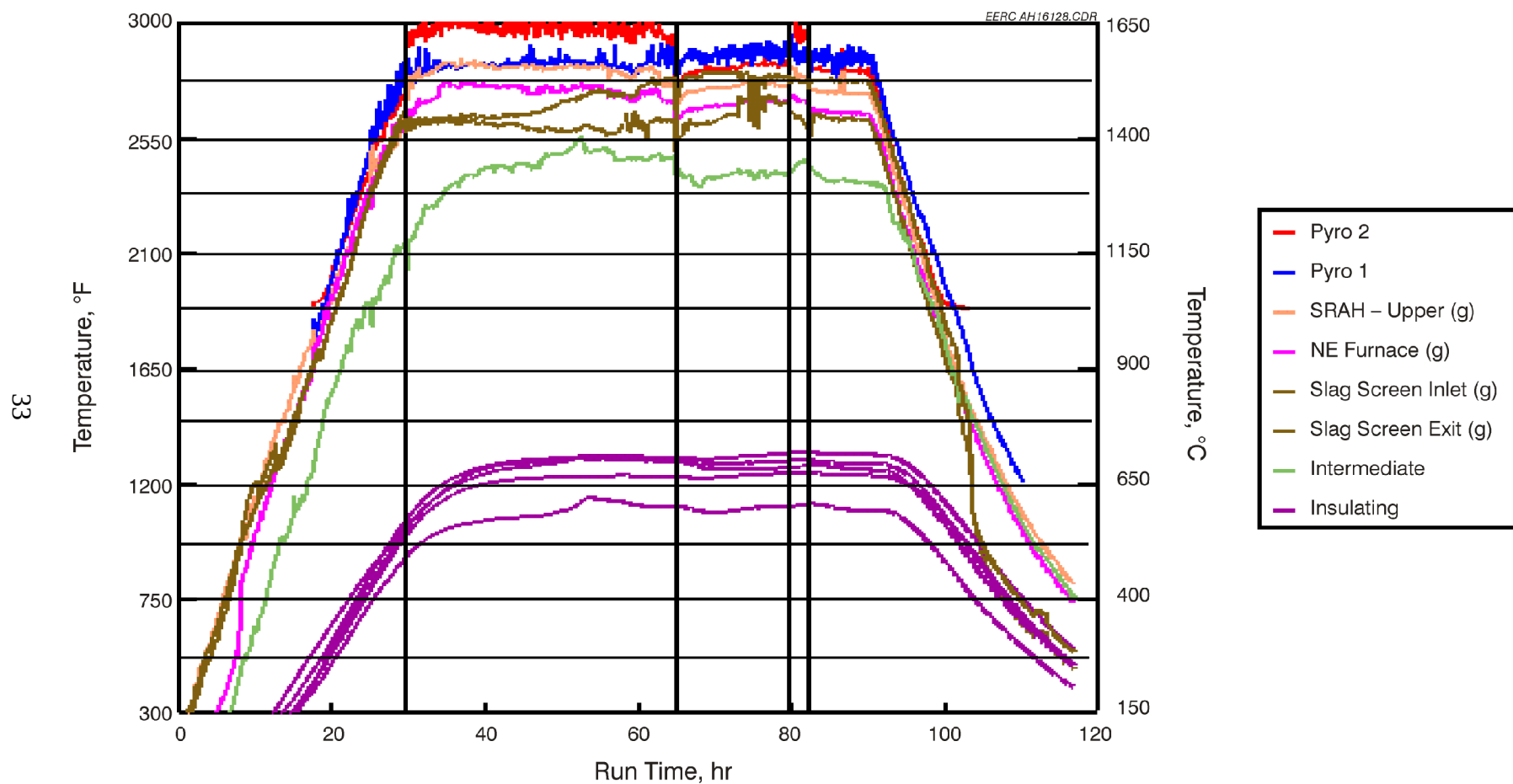


Figure 3-6. Furnace and slag screen temperatures versus run time for the February 1999 test, SFS-RH7-0299.

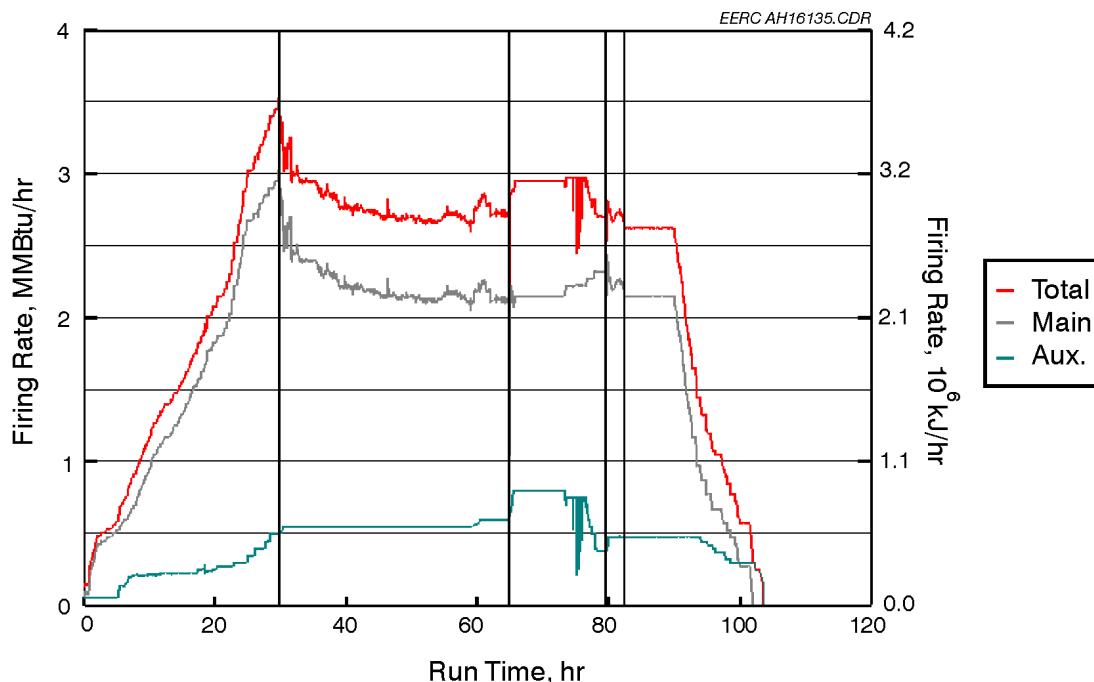


Figure 3-7. Slagging furnace firing rate versus run time for the February 1999 test, SFS-RH7-0299.

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

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

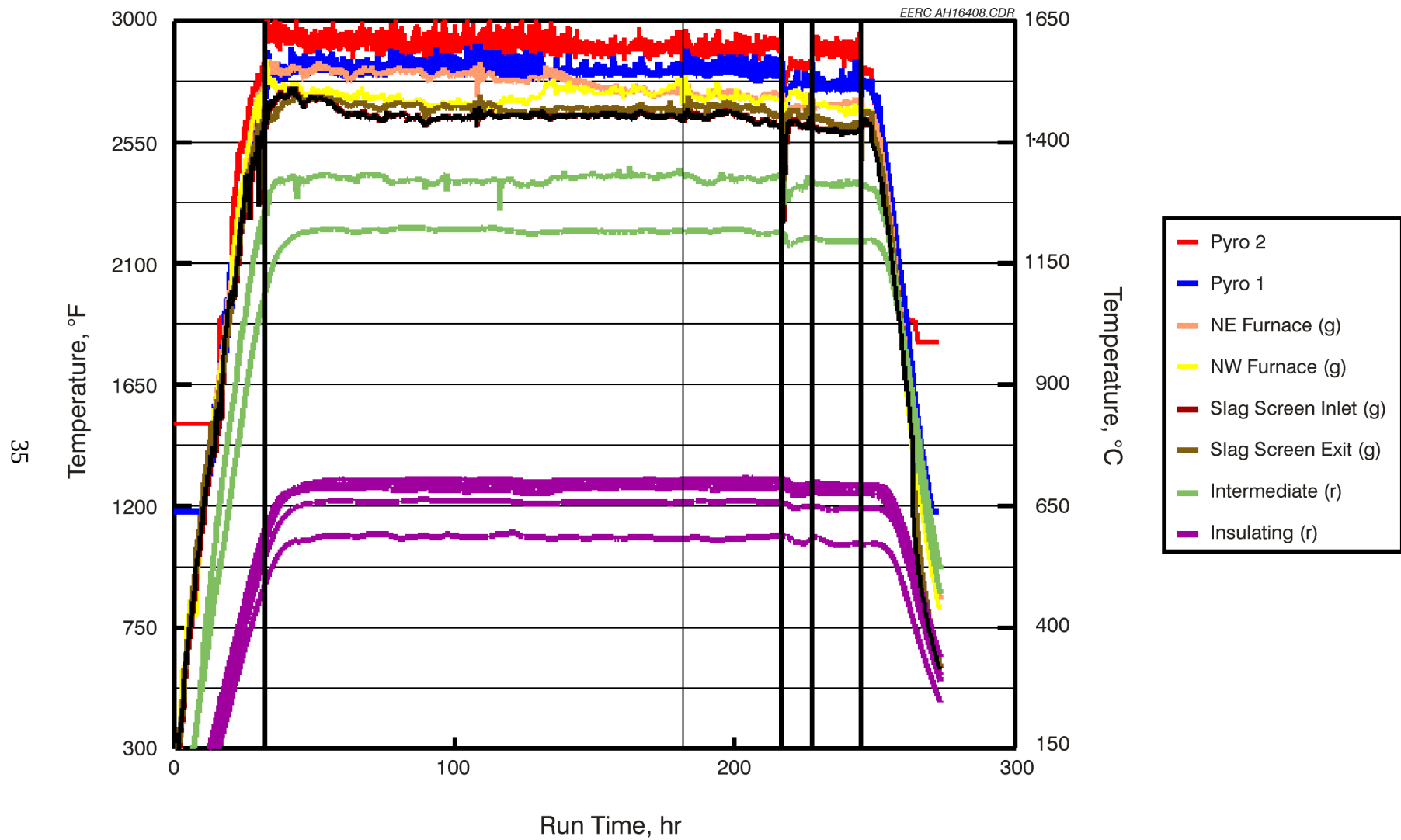


Figure 3-8. Furnace and slag screen temperatures versus run time for the April 1999 test, SFS-RH8-0399.

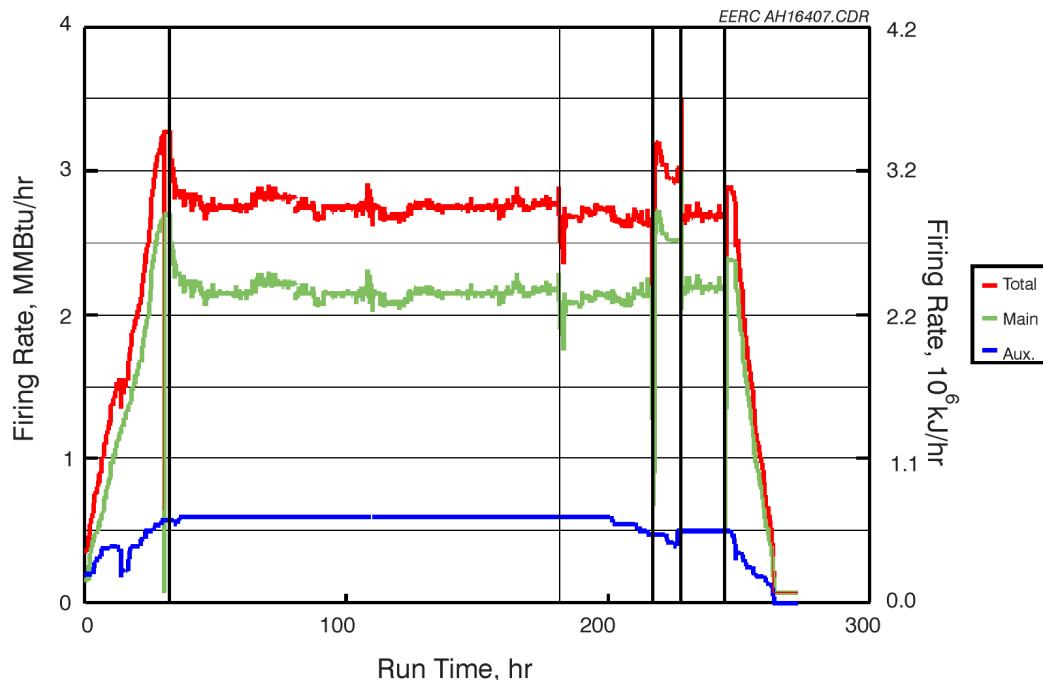


Figure 3-9. Slagging furnace firing rate versus run time for the April 1999 test, SFS-RH8-0399.

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

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

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

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

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

Main and Auxiliary Burners

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

Slag Screen Performance and Slag Analysis

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

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

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



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

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

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

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

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

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

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



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

TABLE 3-3

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

¹ Oxide concentrations normalized to an SO₃-free basis.

² SO₃ concentrations normalized with other oxides.

TABLE 3-4

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

¹ Oxide concentrations normalized to a SO₃-free basis.

² SO₃ concentrations normalized with other oxides.

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

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

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

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

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

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

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

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

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

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

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

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

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

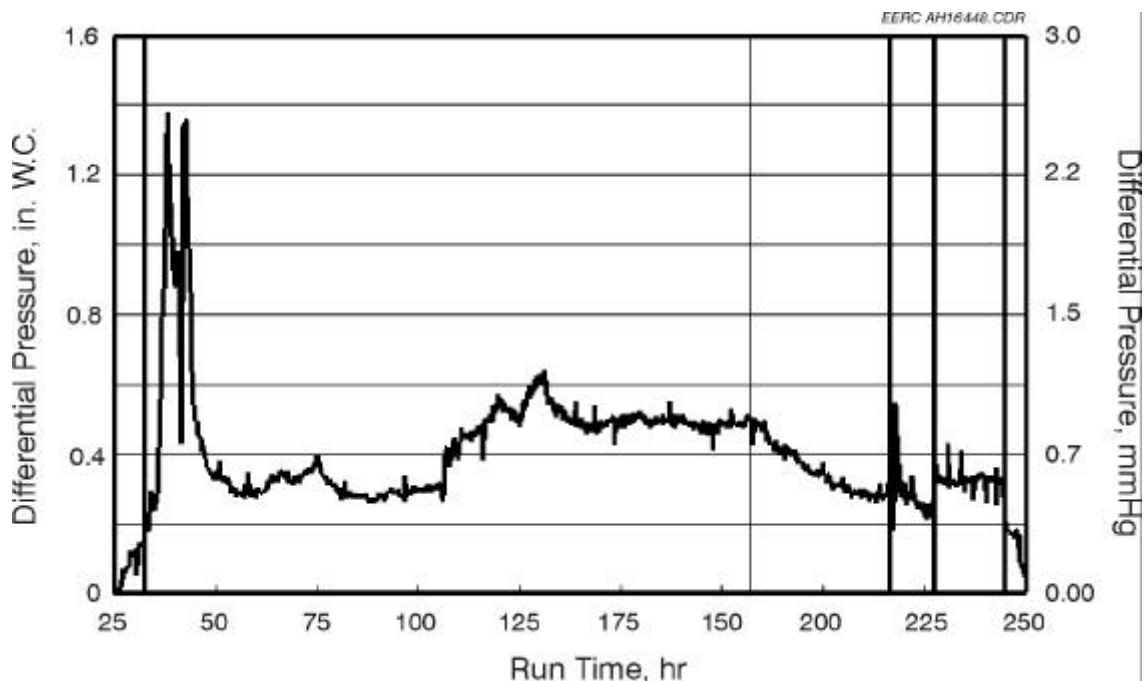


Figure 3-12. Slag screen differential pressure versus run time for the April 1999 test, SFS-RH8-0399.

TABLE 3-5

April Kentucky Coal Ash and Slag Tap Samples

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

¹ Oxide concentrations normalized to 100% closure.

² SO₃-free basis.

³ Not measured.

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

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

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

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

Dilution/Quench Zone

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

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



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

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

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

Process Air Preheaters

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

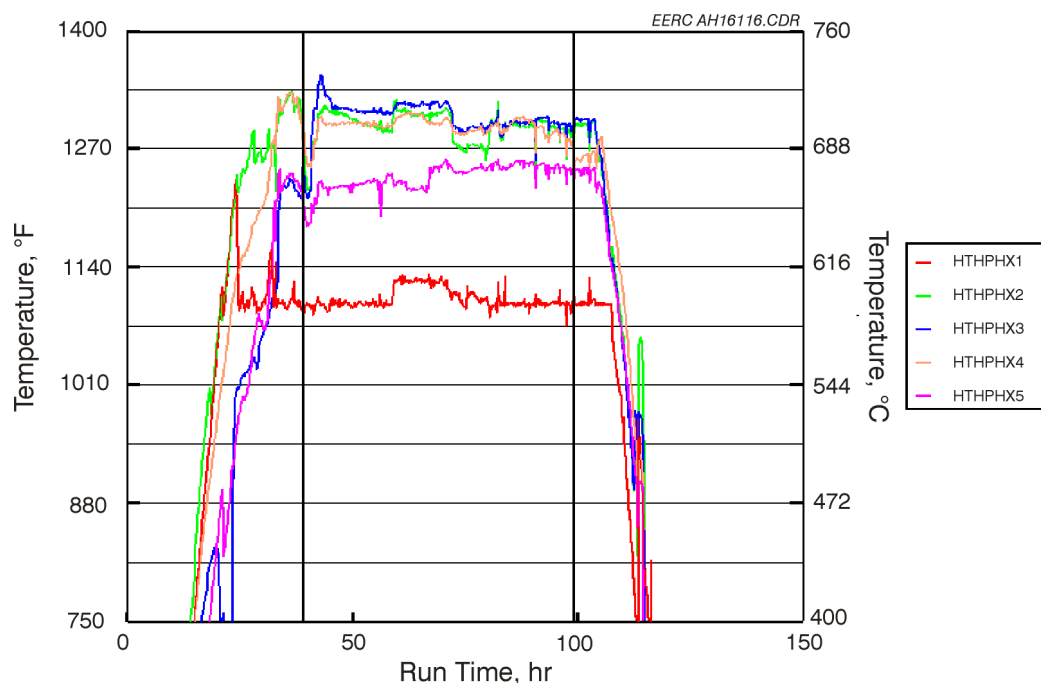


Figure 3-14. Process air preheater temperatures versus run time for the January test, SFS-RH6-0199.

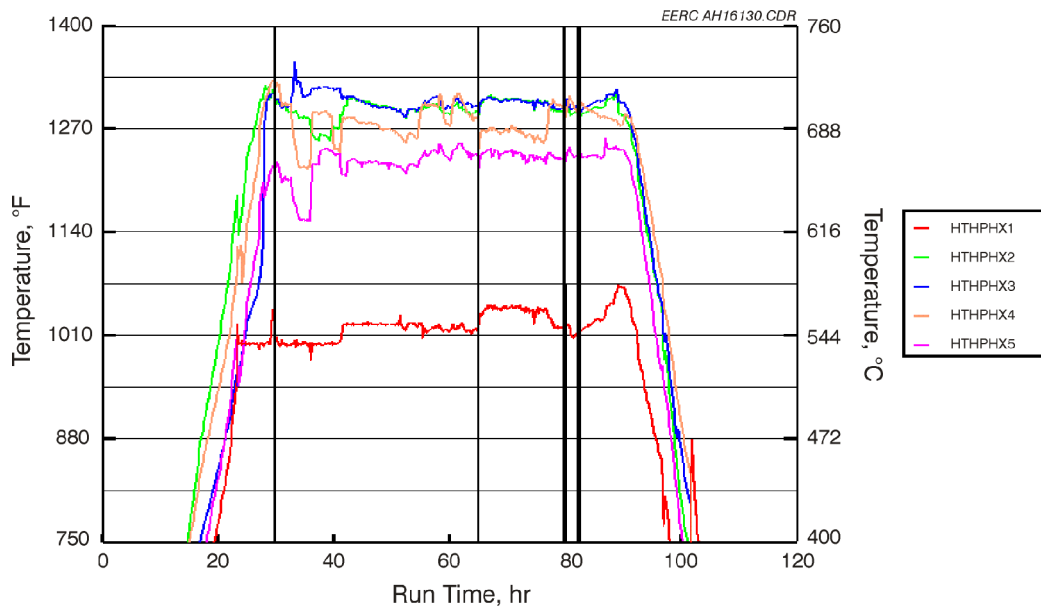


Figure 3-15. Process air preheater temperatures versus run time for the February test, SFS-RH7-0299.

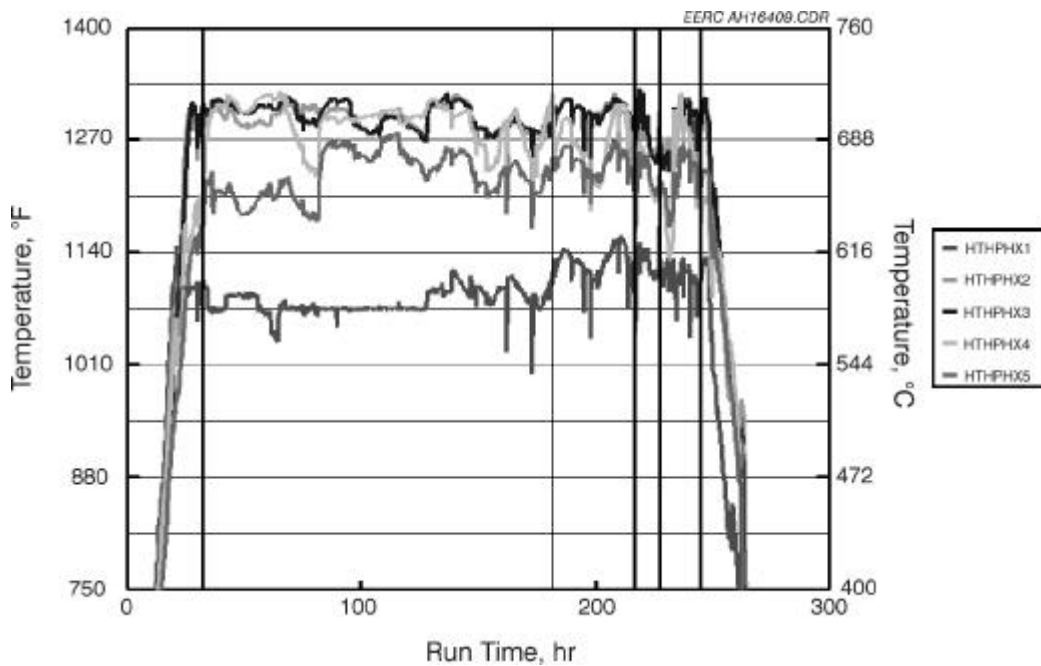


Figure 3-16. Process air preheater temperatures versus run time for the April test, SFS-RH8-0399.

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

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

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

Particulate Emissions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

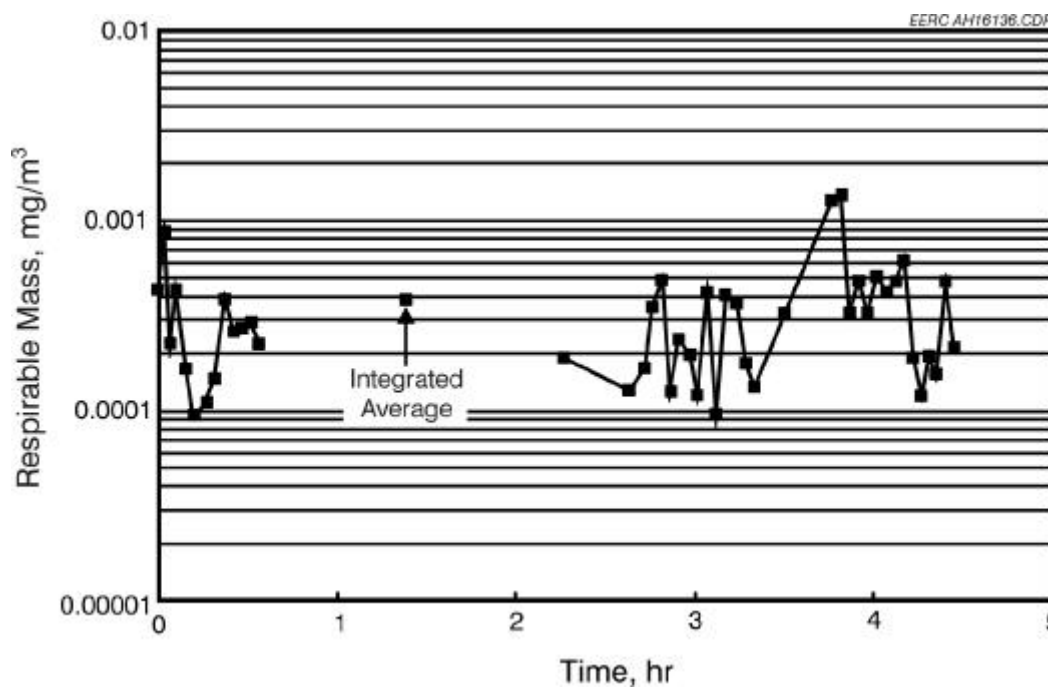
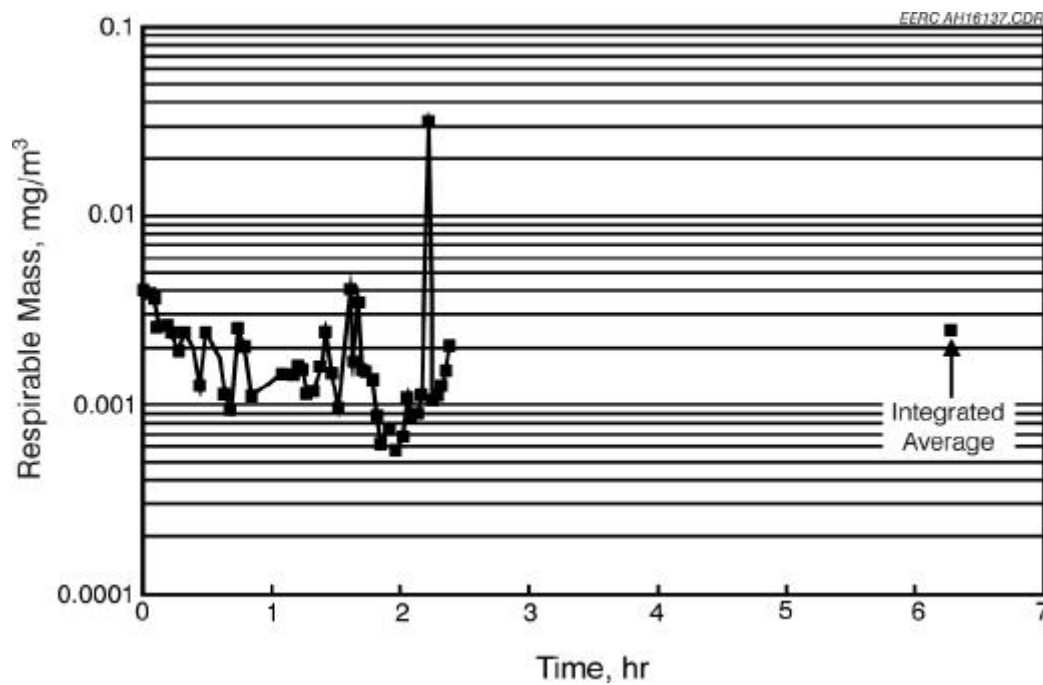


Figure 3-17. Respirable mass emission data for the January (top) and February (bottom) tests.

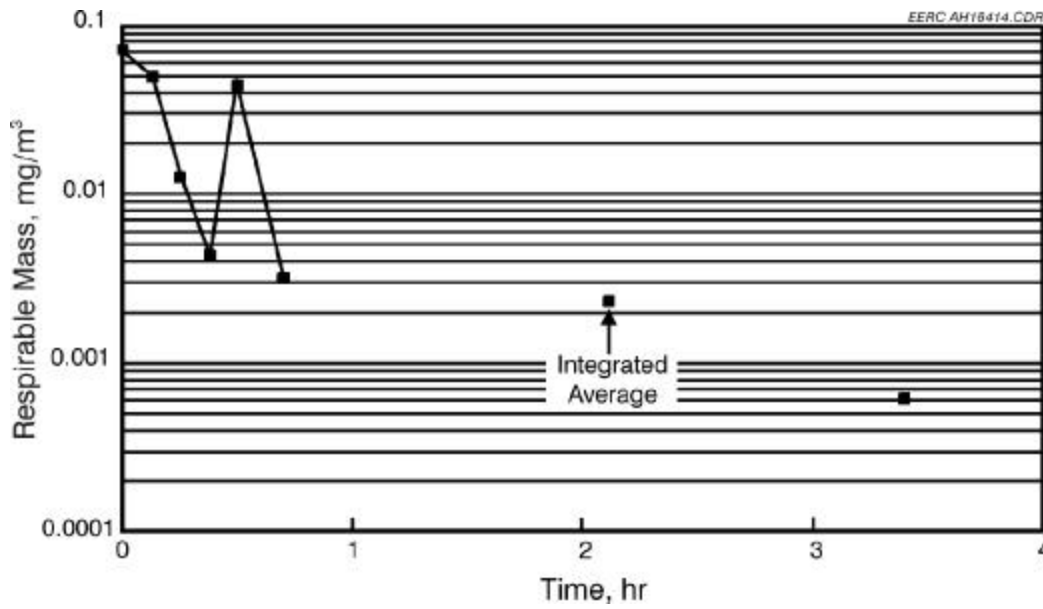


Figure 3-18. Respirable mass emission data for the April test.

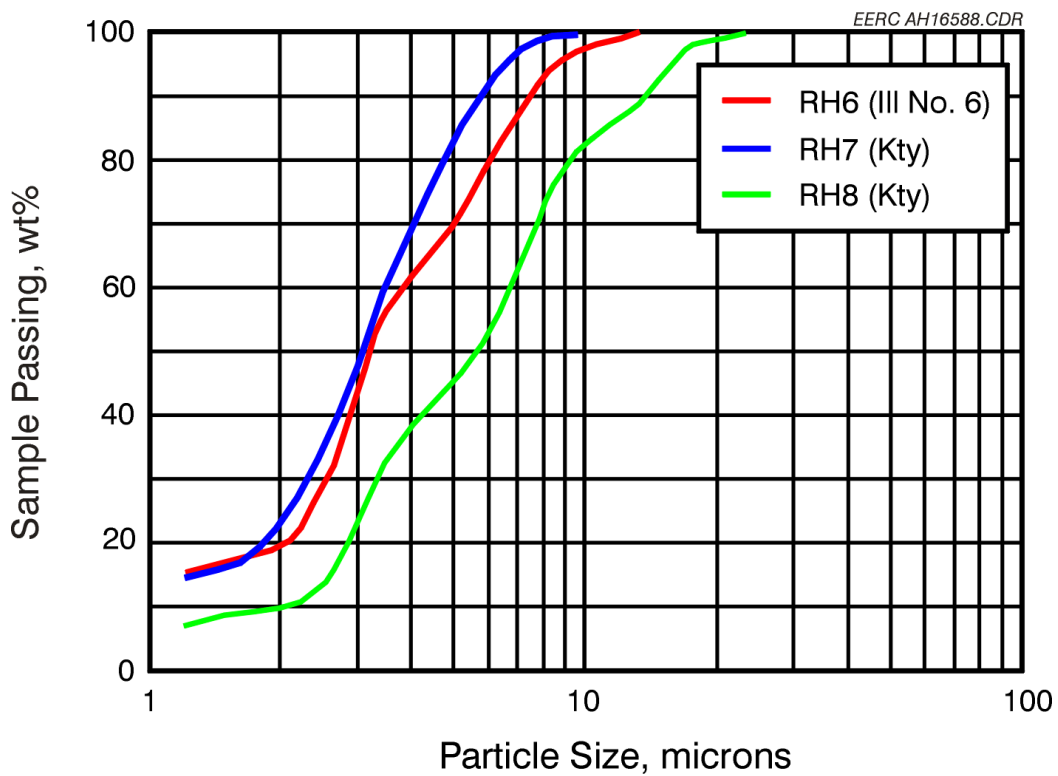


Figure 3-19. Baghouse hopper ash particle-size data.

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

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

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

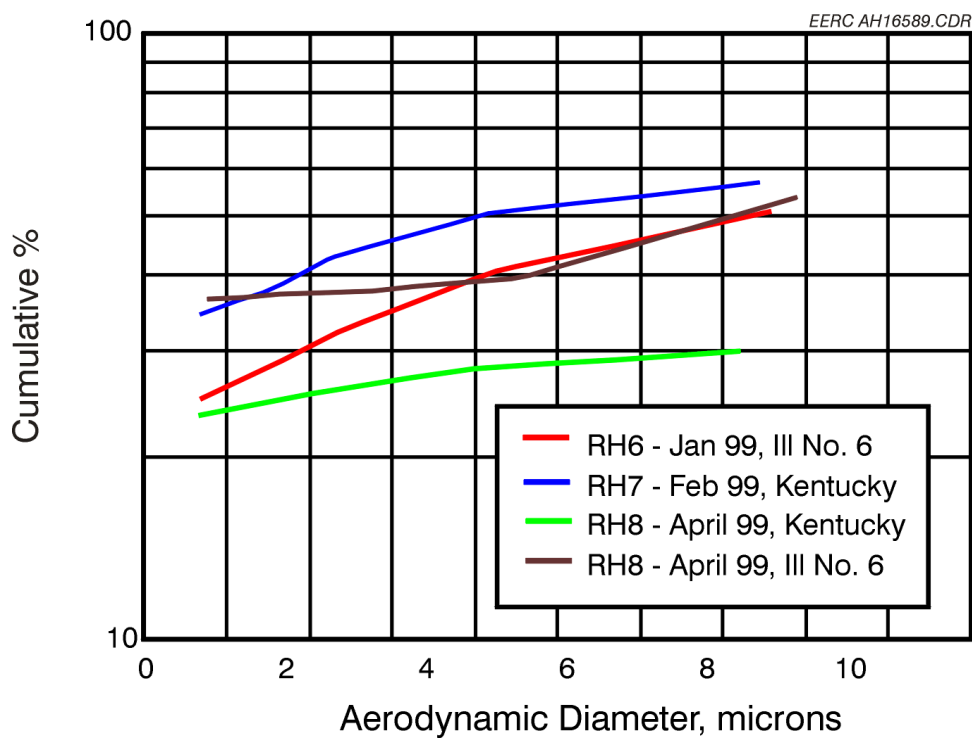


Figure 3-20. Multicyclone data resulting from baghouse inlet sampling.

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

Carbon Monoxide Emissions

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

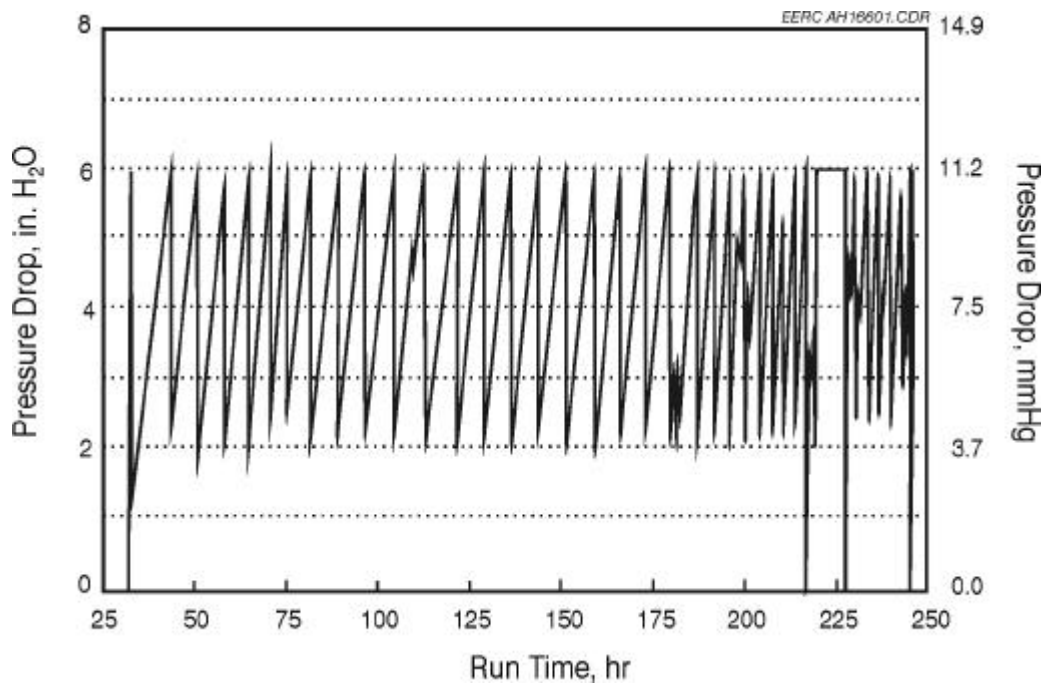


Figure 3-21. Baghouse differential pressure versus run time for the April test.

TABLE 3-6

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

NO_x Emissions

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

SO₂ Emissions

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

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

3.1.2 CAH Tube Bank Performance

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

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

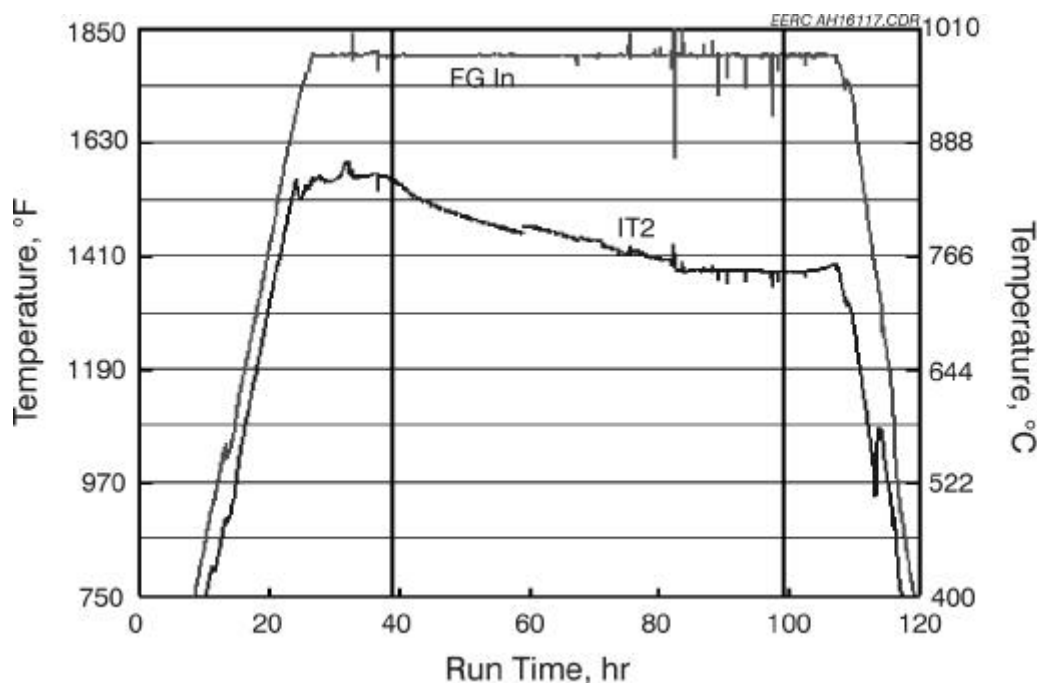


Figure 3-22. CAH tube surface and flue gas temperatures versus run time for the January test, SFS-RH6-0199.

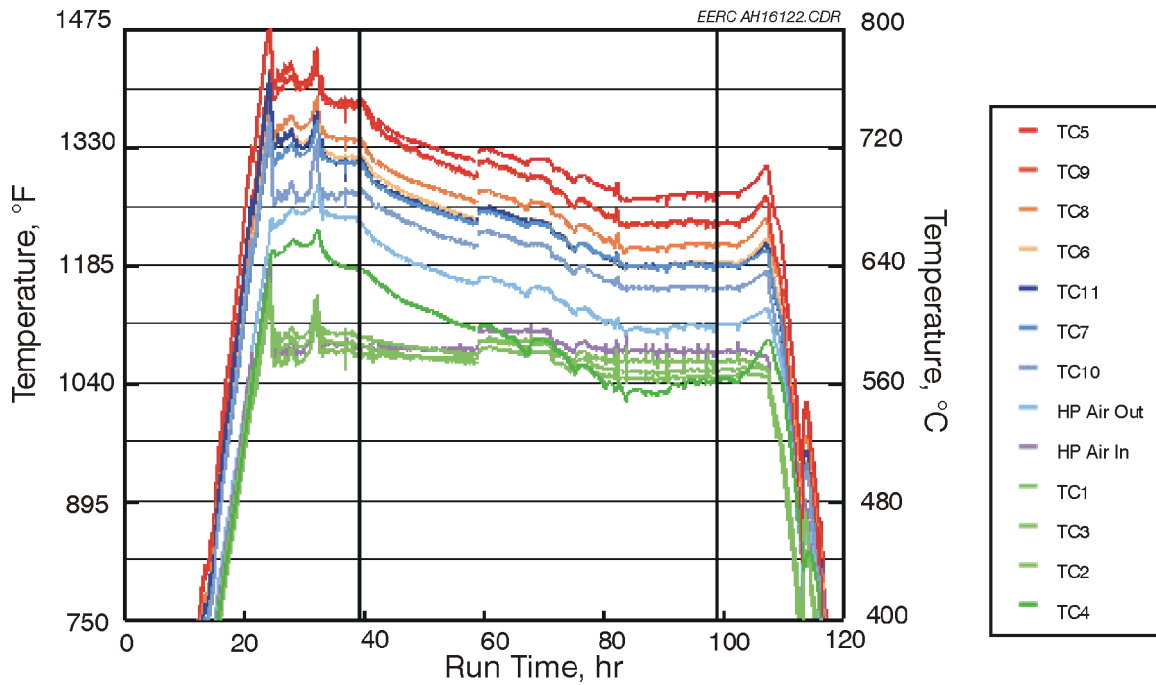


Figure 3-23. CAH process air temperatures versus run time for the January test, SFS-RH6-0199.

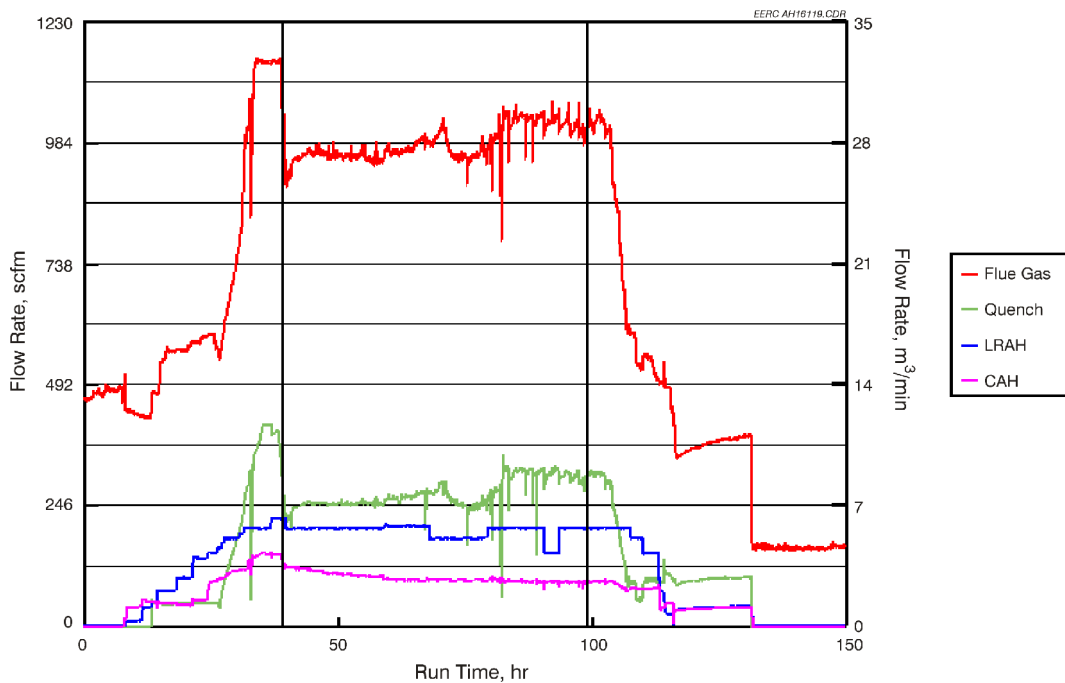


Figure 3-24. CAH process air, RAH process air, quench gas, and flue gas flow rates versus run time for the January test, SFS-RH6-0199.

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

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

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

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

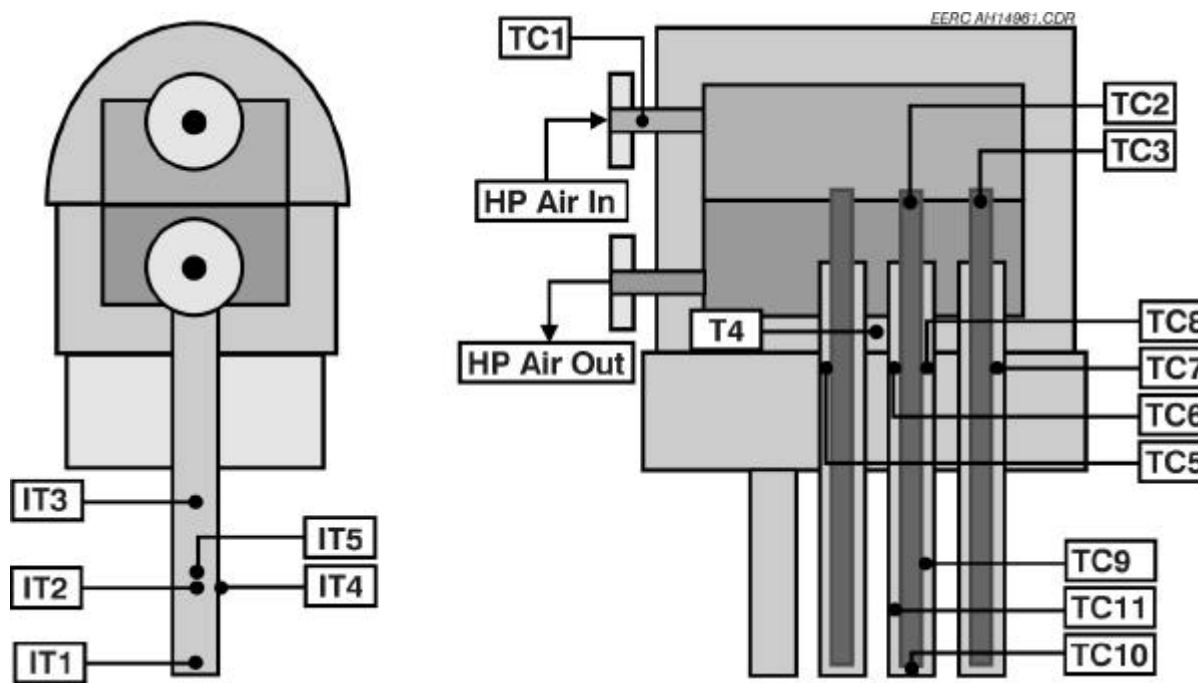


Figure 3-25. Thermocouple locations in the CAH tube bank.

TABLE 3-7

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

¹ Thermocouple locations are illustrated in Figure 3-25.

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

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

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

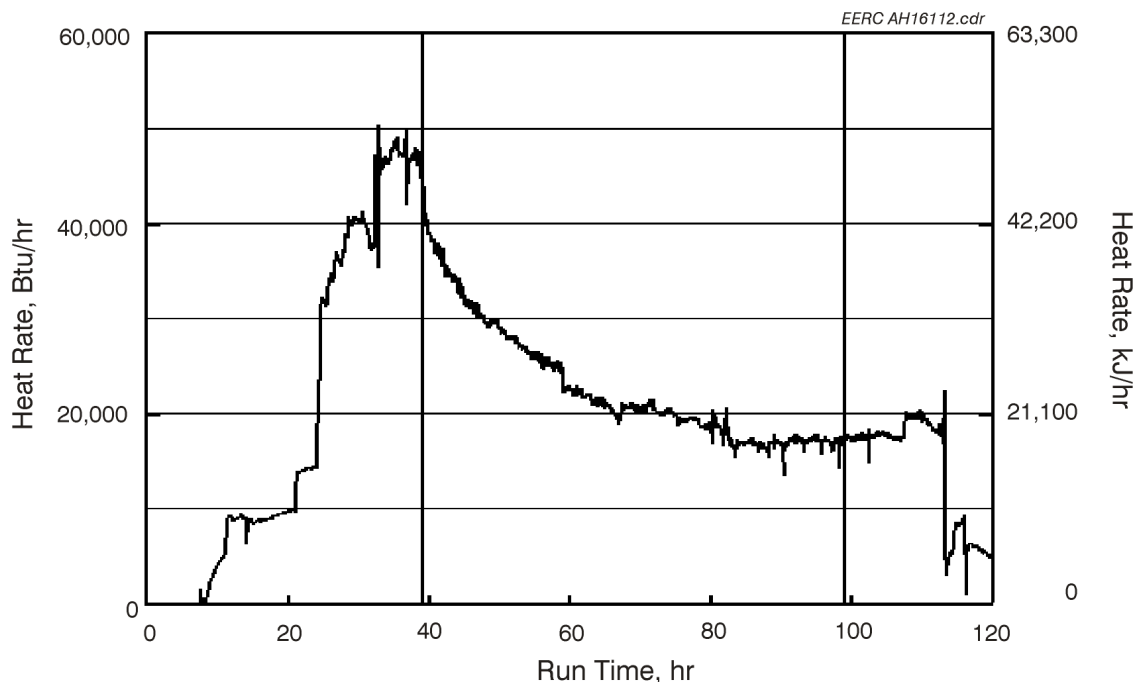


Figure 3-26. CAH heat recovery versus run time for the January test, SFS-RH6-0199.

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

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

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

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