Status Of Proof-Of-Concept Testing At The Coal-Fired - Flow Facility - 1993

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STATUS OF PROOF-OF-CONCEPT TESTING AT THE COAL-FIRED-FLOW FACILITY - 1993*

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ABSTRACT

Proof-of-concept (POC) testing, and collection and evaluation of data continued at the Coal-Fired-Flow Facility during the past year. Following four preliminary tests firing Rosebud coal in 1991 to establish base conditions for the Rosebud coal POC tests, three POC tests were run in 1992, and a fourth test early in 1993.

Major equipment additions or modifications included installation of a wet electrostatic precipitator (ESP), which replaced a badly deteriorated venturi. This component also provides improved capability to meet Tennessee pollution regulations while operating the dry ESP and/or baghouse off design, or if one of these two control devices does not function properly. Improvements were also made to the dry ESP prior to the 1993 test, which appear to have improved the performance of this equipment. The shaft failed in the pulverizer, which had been manufactured in 1933. It was replaced in 1992, but failed again during LMF4-H in 1993. The cause of the failure is being examined and preparations are being made to replace the shaft. This paper will present an overview of the major results obtained during the Rosebud coal POC tests, including the performance of the dry and wet electrostatic precipitators. Differences between the Rosebud and Illinois coals will be described, *but it is emphasized that these observations are based on incomplete results for the Rosebud coal.*

INTRODUCTION

The University of Tennessee Space Institute (UTSI) began preparation for long term Proof-of-Concept (POC) testing with coal when they began the first coal fired MHD experiments in 1971. The first POC program was initiated in 1987 while burning Illinois #6 coal. This program was completed late in 1990,[1] with a test to simulate the Scholz retrofit conditions in 1991. These tests were followed by four tests during which Rosebud coal from Montana was fired at different conditions to establish the conditions for the Rosebud POC Tests, which began with LMF5-E in 1992. Most of the nominal test conditions for the Rosebud coal are the same as for the Illinois coal tests. Nominal thermal input, stoichiometry, nitrogen to oxygen, total seed throughput, the form of the seed (potassium carbonate) and other parameters are essentially the same for both coals. The operating parameter ranges are similar, although as results are obtained, somewhat different operating ranges may be required to provide additional data. One difference is the method of adding the potassium carbonate seed. Dry K_2CO_3 was mixed with the coal in the pulverizer and thus fed with the coal for the Illinois coal tests. A 47% solution of K_2CO_3 is being used for the Rosebud coal program. This approach will provide more precise control and more rapid changes of the feed rate. During the Illinois #6 the coal/seed mixture was fed through large storage and feed tanks before being fed to the combustor. Therefore for this method there is a long delay between the time the miture ratio is adjusted and when it arrives at the combustor. Some changing of the seed/coal ratios also can occur as the mixture travels through the baghouse and feed and storage tanks. Using similar conditions permits the comparison of the major differences in the coals, which are primarily the reactivity and moisture levels of the coals, the ash composition and the sulfur levels. This paper will highlight some of the results of the Rosebud POC tests, with emphasis on some *preliminary observations* of differences in test results for the two coals. We stress that these are preliminary and the continuing Rosebud tests may change some of these comparisons.

The primary differences between the results thus far include:

1. Reactivity and moisture levels. Obviously, this difference was known before the test program began, but it did lead to significant

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modifications to the coal preparation system to permit safe operation while drying the high moisture Rosebud coal to levels that were needed for satisfactory feed rates. The modifications have been described earlier and have performed well.

2. Coal ash composition. These differences resulted in different viscosity characteristics and thus in tapping differences at the primary furnace as well as slag layer thickness and thermal conductivity of the slag.

3. The ignition temperatures of the gas mixture at the secondary combustor were different - higher in the case of the Rosebud coal.

4. Properties and appearance of the deposits.

5. The performance of the baghouse and ESP.

6. Nitrogen Oxide levels.

These differences will be discussed in the paper along with our initial preliminary assessment of some of the reasons for the differences.

FACILITY MODIFICATIONS

The coal preparation system was modified extensively to pulverize the more reactive Rosebud coal safely and to assure that this coal, which contains about twice the moisture of the Illinois coal could be adequately dried. The background for this change and a detailed description were given in the 1991 Symposium.[2,3] Basically, the change resulted in a higher drying temperature, which required a new heater, modifications to the pulverizer, and additional components to inert the coal while pulverizing and to recycle and reduce the moisture in the inert gas. This system has been in operation throughout the Rosebud coal testing and has performed well.

Another major change was the addition of the wet electrostatic precipitator (ESP). The wet ESP was procured from the North American Air Pollution Company and installed in the summer of 1992. It contains a conditioning system, a spray section, and a collector section. A rotary drum filter was added to the wet ESP during the LMF5-G test. The system is shown in Figures 1 and 2. A detailed description of the wet ESP was presented by Sheth, Holt , Douglas and Thompson.[4] This system replaced an inefficient venturi scrubber which was removed primarily because it had corroded severely. The wet ESP gives us the capability to meet Tennessee air pollution regulations.

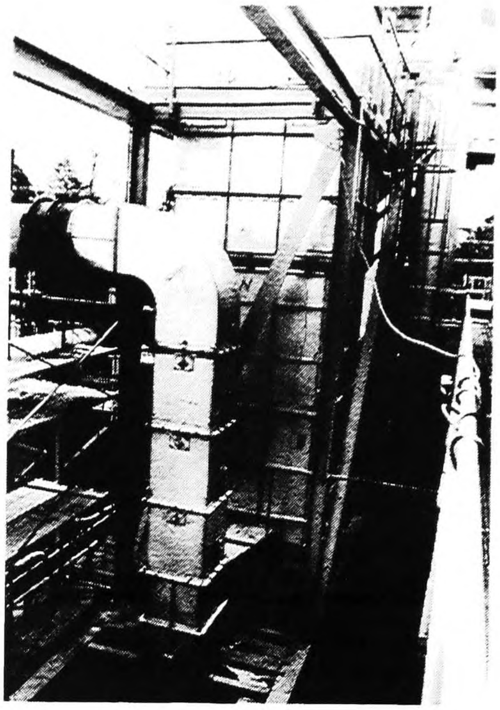

Figure 1. Wet ESP Installed in the CFFF Flow Train

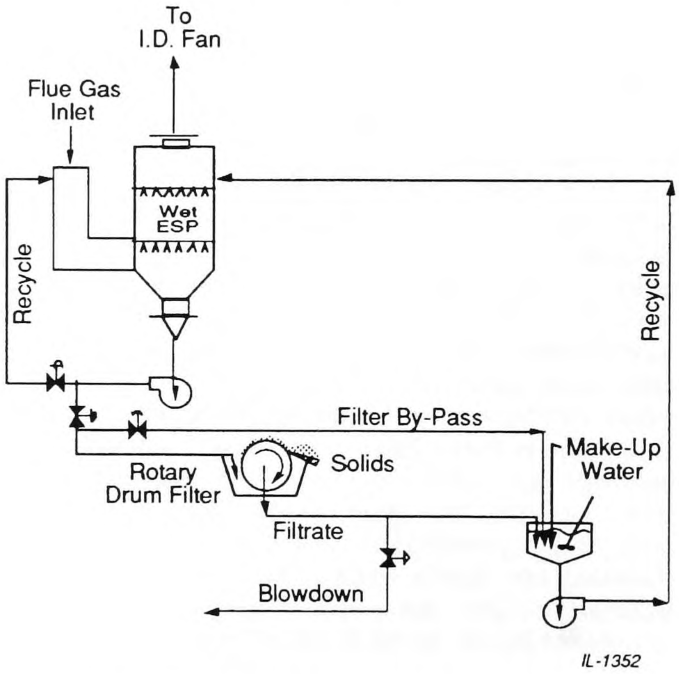

Figure 2. Schematic of Honeycomb of Wet ESP

Wet ESPs are known for their high collection efficiency for submicron particles. Wet ESPs and dry ESPs differ primarily in their mechanism for removing the collected particulate. In a dry system, a timed sequence of mechanical rapping or vibrating are used to remove the ash from the collection surfaces. During these rapping periods, the ash falls from the collection plates or discharge electrodes into a hopper; however, reentrainment of particulate into the gas stream occurs which reduces collection efficiency. In a wet system, the collected particulate is washed from the surfaces with water and little or no reentrainment occurs.

Some of the disadvantages normally associated with using wet ESP systems are not applicable for MHD systems. Since the spent seed must be regenerated and since the seed regeneration processes begin with a dissolution step, the solution/slurry exiting the wet ESP may eliminate one of the required processing steps. In addition, for conditions where potassium carbonate and potassium sulfate are present in the collected seed, this system can be used to separate the K_2CO_3 from the K_2SO_4. Since K_2SO_4 has a reduced solubility in the presence of K_2CO_3, a filtration scheme is employed to effect the separation.

TEST RESULTS

Overview

Three LMF5 Proof-of-Concept (POC) tests were conducted in 1992 and thus far in 1993; LMF5-E, LMF5-F, LMF5-G and LMF5-H. LMF5-E was the first test in the Montana Rosebud POC series of tests which is designed to test the downstream components for a total of 2000 hours. Individual test durations on coal were 91 hours for LMF5-E, 290 hours for LMF5-F, 314 hours for LMF5-G and LMF5-H for 88 hours. The LMF5-H test was originally scheduled for 225 hours, but was terminated after just 88 hours when the main pulverizer shaft broke for the second time in two years. The first replacement was done under the supervision of the manufacturer, Babcock and Wilcox Co. and we have contacted them to try to determine the cause of this failure and to oversee the installation of the replacement. The total hours of POC operation for Rosebud coal is 783 hours. The overall objectives remain the same: i.e., to develop technology required for scale up in areas such as heat transfer, emissions control, ash deposition, materials performance, environmental impact etc.

Rosebud Coal and Slag Analyses

Coal samples are sampled and analyzed from incoming shipments and frequently throughout each test. This information is necessary to determine: thermal input, the composition of materials that will produce ash deposits, the potassium to sulfur ratios, and calculate combustion gas composition among other reasons. Analyses for the Rosebud coal composite sample collected during the most recent test, LMF5-G are shown in Table 1. Slag samples collected from the primary furnace slag tap while firing Illinois and Rosebud coals were also analyzed, and Babcock & Wilcox determined the viscosity-temperature relationship at our request. The analyses are shown in Table 2 below, and the viscosity data are shown of Figure 3. This figure indicates that the seeded slag from Rosebud coal seeded with sulfate and collected while injecting carbonate had a lower viscosity than the Illinois coal slag collected while firing a mixture of the coal and carbonate seed.

Table 1. Rosebud Coal Analyses LMF5-G

Ultimate, Wt. %, Dry Basis		Elemental Analysis, Wt. % of Ash (Reported as Oxides)	
Carbon	67.3	SiO_2	42.0
Hydrogen	4.44	Al_2O_3	18.6
Nitrogen	0.89	Fe_2O_3	4.5
Sulfur	0.82	TiO_2	0.9
Ash	10.61	CaO	20.3
Oxygen (by diff)	15.97	MgO	4.1
		Na_2O	0.3
		K_2O	0.8
		SO_3	10.0
		CO_2	N/A
		Cr_2O_3	0.04
		P_2O_5	N/A

Table 2. Slag Elemental Analysis, % by Weight

Constituent	Illinois Coal Slag LMF4-P	Rosebud Coal Slag LMF5-A
SiO_2	43.9	42.9
Al_2O_3	13.4	17.5
Fe_2O_3	15.6	2.9
TiO_2	0.79	0.86
CaO	6.3	20.7
MgO	0.91	3.5
Na_2O	0.32	0.22
K_2O	16.4	12.9
SO_3	0.47	0.3
P_2O_5	N/A	N/A

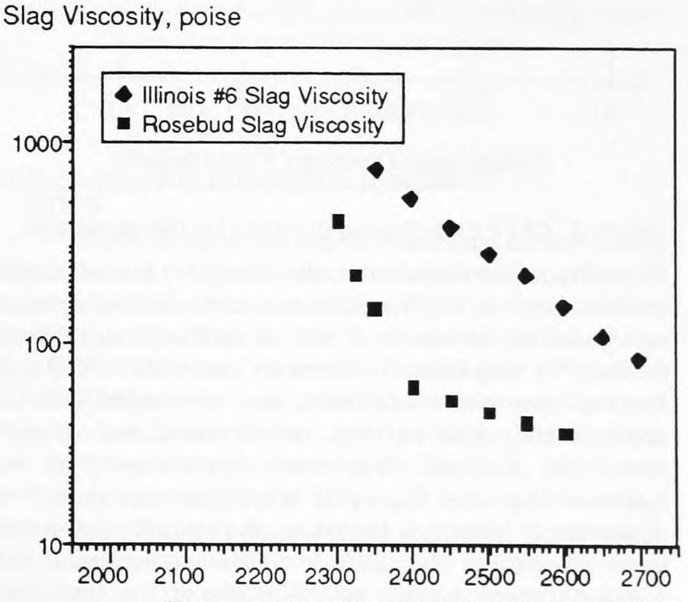

Figure 3. Slag Viscosities for Illinois #6 and Rosebud Coals

Effect on Topping Cycle Components

One significant difference in the topping cycle is that it is difficult to dry the Montana Rosebud coal to a moisture level of 5-6%, whereas the Illinois No. 6 coal was typically dried to 2-3%. This additional moisture reduces the flame temperature and the electrical conductivity of the plasma because of the negative effect of the additional OH radicals formed when water is dissociated.

Test measurements typically have shown a lower diffuser outlet temperature with Rosebud coal than with Illinois No. 6 coal by at least 180°F (100K). This is more than expected because of the additional moisture. The reason for this greater difference can be seen in Figure 4, which shows typical experimental heat fluxes for both Illinois No. 6 and Rosebud coals. The level of heat loss in the first meter of the flow train combustor is roughly twice as high for the Illinois No. 6 coal as for the Rosebud coal. Further, the slag layer thickness on the combustor and, in fact, on the entire upstream flow train simulation is approximately half as thick on Rosebud coal as with Illinois No. 6 coal. The lower slag viscosity for the Rosebud coal (see Figure 3) is a major reason for this difference in slag layer thickness and heat fluxes. If one were comparing the coals for MHD applications, the additional heat losses to the walls of the upstream components would be an adverse factor. However, the thinner slag layer is favorable for power generation because there will be less current leakage through the slag layer.

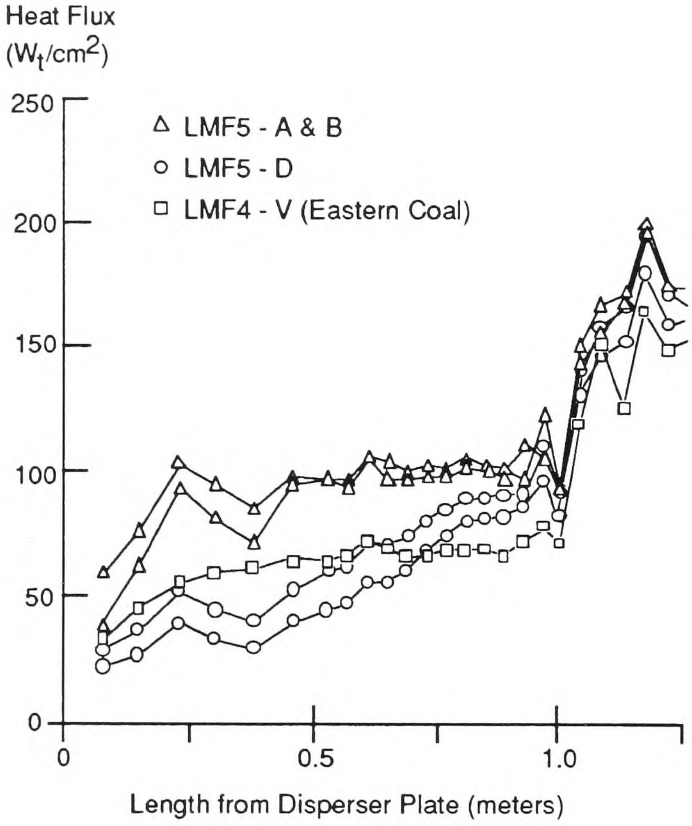

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Figure 4. CFFF LMF Upstream Heat Flux Measurements

Effect of Potassium Compounds on Secondary Combustion

Problems have occasionally been experienced in igniting the secondary combustor during the LMF5 test series, and test results indicate that the problem may be due to several factors including primary stoichiometry, inlet gas temperature and flame suppression by potassium species in the flue gas. During last year, some work was done on the effect of K_2CO_3 addition. Potassium carbonate is now supplied to the primary combustor in a 47% solution. When seed solution flow is started with the indicated gas temperature entering the secondary combustor lower than about 1600°F, secondary combustor performance often degrades dramatically. This phenomenon has not been observed at indicated secondary combustor inlet gas temperatures above about 1650°F. A typical example occurred during LMF5-E. Coal firing was established with no seed flow at about 1510°F and seed flow was started at about 1710°F. Prior to starting seed flow, secondary combustor operation was normal; however, immediately after introduction of seed the secondary combustor flame was strongly influenced, increasing downstream CO levels. Normal operation resumed when the seed flow was turned off. The same phenomenon was repeated on two other occasions during this test and again during LMF5-H, when the seed flow was turned on and off for brief periods. Potassium carbonate solution flow rate and secondary combustor outlet CO concentration during LMF 5-E are plotted in Figure 5. The secondary combustor inlet gas temperature indicated by

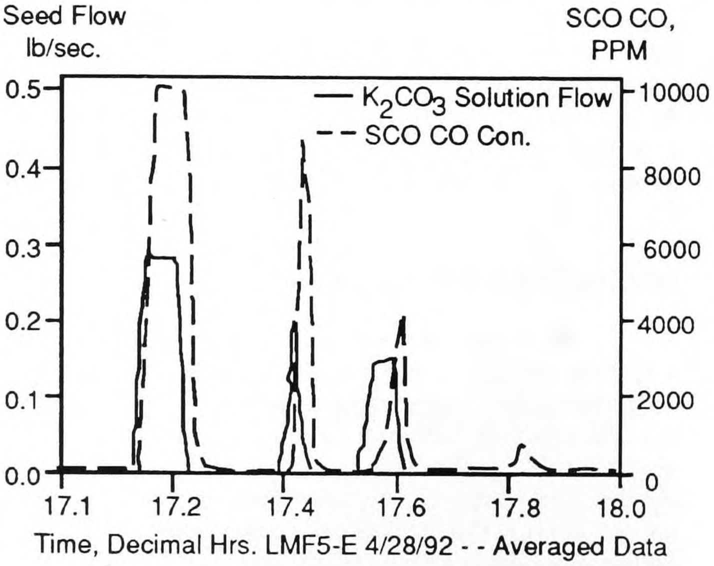

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Figure 5. Effect of Seed on Secondary Combustor Outlet CO (Inlet Gas Temperature Approximately 1800°F/Secondary Air Temperature Approximately 470°F)

thermocouples during this period was about 1600°F. The actual gas temperature corrected for thermocouple radiation losses was probably about 1800°F. Secondary air temperature was around 470°F, providing an estimated mixture temperature (not including heat of combustion) of about 1520°F. This is well above the normal minimum ignition temperature for CO, which is about 1250°F. Normal secondary combustor operation with seed flow was established when the indicated secondary combustor inlet gas temperature reached about 1660°F.

Suppression of flames by potassium is a well known phenomenon, and chemical kinetics studies indicate that both potassium and sulfur can inhibit flame propagation under some conditions. The most likely mechanism for flame inhibition by potassium is

$$KOH + H \rightleftharpoons K + H_2O$$

and

$$K + OH + M \rightleftharpoons KOH + M,$$

where M is a third body, such as N_2, H_2O, or H_2. These reactions inhibit CO oxidation by removing OH radicals from the flame.

Equilibrium chemistry calculations indicate that the concentration of KOH in the reducing gas prior to secondary combustion is about 0.2% at 1800°F for typical seed flow rates. KOH vapor is in equilibrium with condensed K_2CO_3, and the equilibrium concentration of KOH does not change after secondary combustion, provided that a significant amount of K_2CO_3 remains after secondary combustion ($K_2/S > 1.1$). For the case where there is no K_2CO_3 after secondary combustion ($K_2/S < 1.1$), KOH concentration is less than 5 ppm after secondary combustion. The absence of KOH after secondary combustion for low K_2/S conditions provides a possible explanation for the low frequency of secondary combustor problems experienced during LMF4 testing with high sulfur Illinois coal, as compared to the LMF5 results.

The predicted effect of KOH concentration on secondary combustor flame propagation has been modeled using the NASA GCKP84 chemical kinetics code. The system was modeled as an adiabatic plug flow reactor, with the flue gas and secondary air being instantaneously mixed at position X=0. The two potassium reactions discussed above were added to a standard set of reactions for CO oxidation. For an initial mixture temperature of 1520°F (1100K), no ignition delay was predicted; however, for a mixture temperature of 1340°F (1000K), a significant ignition delay was predicted, as shown in Figure 6. It should be noted that in the real secondary combustor the mixing is not instantaneous and there is significant heat loss from the flame; both of these factors would increase the ignition delay.

A literature search is being conducted to gather information on potassium and sulfur reactions for use in secondary combustor chemical kinetics modeling. Kinetics studies of the sodium-sulfur system have been performed, and results are available in the literature. The kinetics of the potassium-sulfur system are expected to be very similar to the sodium-sulfur kinetics, but no study of potassium-sulfur interactions has been performed. Reliable, potassium-sulfur kinetics data are required to accurately predict secondary combustor performance, and potassium-sulfur kinetics is also important in the formation of NOx and SO_2. Therefore, bench scale experiments will be conducted at UTSI to obtain the required data.

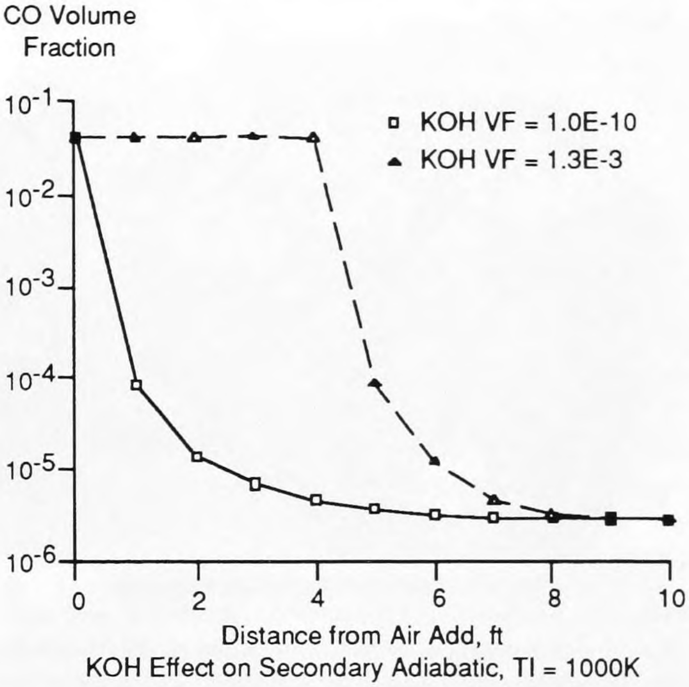

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Figure 6. Calculated CO Concentration versus Distance from Secondary Air Injection Point

POLLUTION CONTROL

Particulates - Wet Electrostatic Precipitator

One of the major efforts in pollution control during 1992 was the installation and preliminary shakedown of the wet electrostatic precipitator (ESP). Of particular significance was the fact that a major component of the Wet ESP, the rotary drum filter, arrived at UTSI after LMF5-G began and was installed and made operational while the low mass flow train was operating. The wet ESP was installed to replace the venturi scrubber, which had corroded severely and was ineffective in meeting Tennessee regulations on start up and when the dry ESP and baghouse were operating off design or were ineffective. The wet ESP also offers some advantages for integrating into an MHD system, since the seed regeneration processes begin with a dissolution step, the solution/slurry exiting a wet ESP may eliminate a processing step.

The original design for the WESP system included a venturi rod deck section where the gas would be humidified and cooled by recirculated water spray. In addition, particles with diameters larger than 5 micrometers would be removed by the venturi rod deck. Initial testing resulted in substantial deposition in the rod deck section which led to blockage of the flow passage (see Figure 7). Since the particulate removed by the rod deck section consisted principally of particles larger than 5 microns (which are easily collected by a WESP), the rods were removed. The spray system remains in place to humidify the gas.

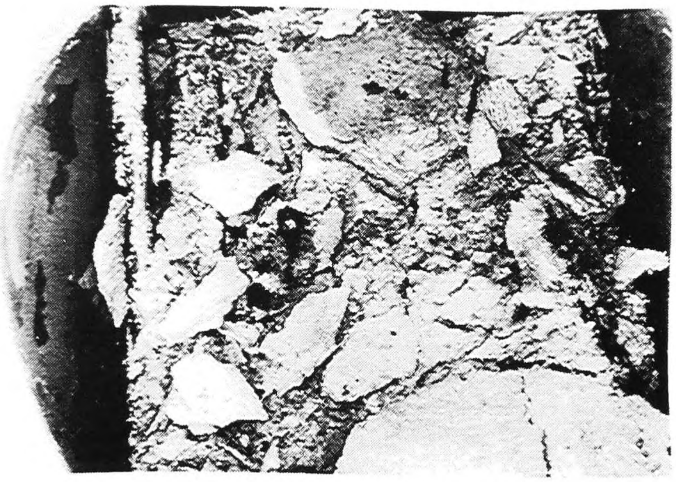


Figure 7. Wet ESP Rod Deck Pluggage

Initial testing of this system began during LMF5-H. Dust loading measurements at the ID fan outlet to the stack were .0069 lb/MBtu, well under NSPS, with 31%, 48% and 21% of the total gas flow passing through the baghouse, dry ESP and wet ESP, respectively. This also is well under Tennessee regulations. The wet ESP also met Tennessee regulations with more than 98% (13350 ACFM) of the total flow passing through it. Under these conditions, emissions were 0.138 lb/MBtu, although inlet dust loading was well under normal loadings. At a flow of 5230 ACFM, emissions were 0.106 lb/MBtu, above NSPS. Deposition of crystalline K_2SO_4 was observed on the electrodes, which may have been at least partly responsible for the lower than expected performance. We shall continue testing and believe performance of this system can be improved significantly at the lower flow rates with minor operating condition changes.

Particulate - Baghouse

The CFFF baghouse was operated during all Rosebud coal tests. As in previous tests, the bags were cleaned using reverse air with sonic horn assist. The nominal filtration velocity through the Gore-Tex bags is 2 ft/min. Emissions from the baghouse ranged from 0.0003 - 0.005 lb/MBtu which is well below the NSPS allowable limit of 0.03 lb/MBtu. Emissions were 0.0005 and 0.0006 lb/MBtu for the two tests completed during LMF5-H earlier this year.

The initial 24 hours of operation during LMF5-E were conducted using oil-firing only which produced a much higher moisture content flue gas. The outlet damper to the baghouse apparently leaked during this period and the bags were thoroughly soaked with condensate. Since both potassium carbonate and potassium sulfate are water soluble, recrystallization of these salts in the fabric itself resulted in blinding of the fabric.

New Gore-Tex bags were successfully tested during the LMF5-F and LMF5-G tests. Four of the carbon steel thimbles which attach to the bags at the bottom had corroded to the point of failure just prior to the LMF5-F test and were capped, and the baghouse was operated with only 26 bags. Replacement stainless steel thimbles arrived prior to the LMF5-G test, and the baghouse was once again operated with 30 bags.

Short durations between the required cleaning cycles were prevalent during all tests. At 5400 cfm (2 ft/min filtration velocity), the cleaning cycles were required at intervals of less than 30 minutes apart. With tests conducted using the Illinois #6 coal and at much lower K_2/S ratios, 90 minutes between cleaning cycles was normal. The reverse air fan was replaced at the same time as this increase in cleaning cycle frequency; however, the fan is supposedly identical to the previous one. Also, the reverse air ductwork had been replaced with a different design, but this too is not suspected to be causing the problem.

The initial cleaning cycle during the LMF5-G tests was approximately 110 minutes in duration. Residual pressure drop is the pressure drop across the tube sheet immediately after a cleaning cycle. After only a few cleaning cycles the residual pressure drop had increased from 1-2 inches wc to over 5 inches wc. This indicates that the ash is not being removed efficiently from the bags or is being reentrained after the cleaning cycle. After periods when the baghouse was taken off line for several hours for inspection, the initial time between cleaning cycles was approximately 90 minutes (see Figure 8) but continually degraded afterwards. Also, cleaning the bags two or three times instead of only once also improved the bag condition. Gore-Tex recommended reduced reverse air flow, which was tried during LMF5-H, but which was not successful. Gore-Tex is considering other approaches.

Particulate - Dry Electrostatic Precipitator

The dry ESP was operated during the four Rosebud POC tests. Performance of the device was

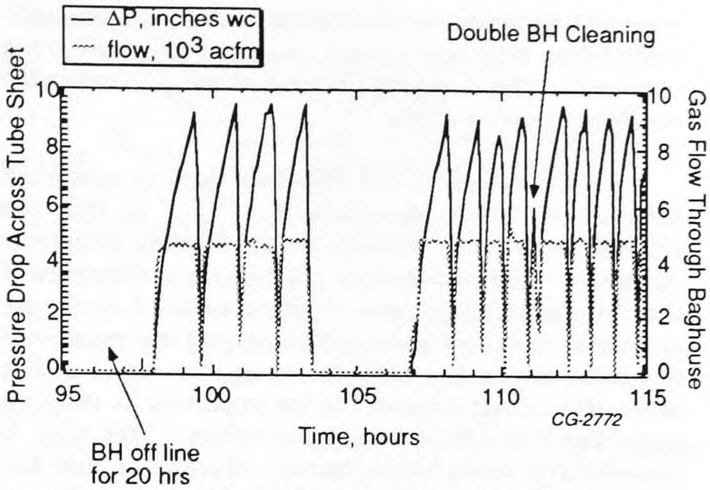


Figure 8. Typical Baghouse Operating Conditions During LMF5-G

marginal during the first three tests due partially from the high gas flow conditions and a measurable decrease in particle size distribution. To meet the CFFF particulate emission operating permit, the dry ESP was forced to process more than 50% of the flow for most tests.

Emissions from the dry ESP during LMF5-E,F &G when potassium carbonate was used ranged from 0.165 - 0.707 lb/MBtu for gas flows of 8900 - 12600 cfm (see Table 3). The nominal design flow for this ESP is only 6300 cfm; therefore, the efficiency is not expected to be good when tests are conducted at a much higher throughput. The particle size distribution has shown an increase in the number of small particles using Montana Rosebud with a K_2/S of approximately 4.0 compared with the Illinois with a K_2/S ratio of 1.0. The mass mean diameter, as measured by a 5 Stage Series Cyclone sampler, has decreased from 0.7 to 0.2 micrometers, which is likely a contributing factor in the low ESP collection efficiency. This decrease in particle size is assumed to be related to the presence of significant quantities of potassium carbonate in the collected ash.

Table 3. Dry ESP Performance During LMF5-E, F & G

	Gas Flow acfm	SCA	Particulate Emissions lb/MBtu	Efficiency %
LMF5-E	7190	417	0.052	93.2 (coal only)
LMF5-F	9880	304	0.165	96.0
	9720	309	0.273	94.2
	12590	238	0.707	87.8
	11130	270	0.617	89.3
LMF5-G	11800	254	0.689	82.6
	11140	269	0.572	92.0
	10840	277	0.443	93.8
	11160	269	0.470	96.2
	8900	337	0.656	86.9
	8550	351	0.365	93.3
	7210	416	0.405	93.3

During the LMF5-F test, large deposits of ash were formed on the wires and plates which were not removed by the rappers and vibrators (see Figure 9). These deposits are suspected to result from small furnace water leaks which increased the gas moisture content and the moisture was absorbed by potassium carbonate in the ash. Prior to the test, a second set of vibrators (pneumatic) was installed directly on the wire rack of each field, and these vibrators could be operated manually. Post test inspection revealed that these pneumatic vibrators were capable of removing the deposits and capabilities are planned so that either set of vibrators can be used in the automatic timed sequence.

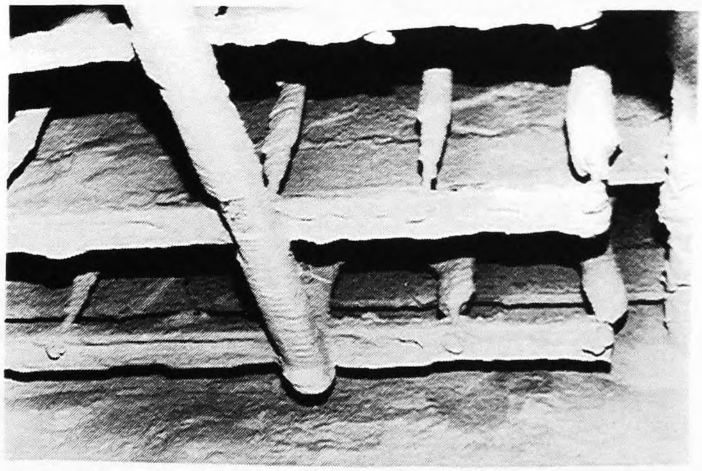


Figure 9. Ash Buildup on Discharge Electrodes in the Dry ESP During LMF5-F

Based upon research conducted by ADA, Inc., we believed the dry ESP efficiency could be increased substantially by replacing the discharge wires with smaller diameter wires. Because of the relatively large diameter electrodes currently installed in the ESP (1/4" round and 5/16" square) it is difficult to maintain high current conditions necessary for high particle collection efficiencies. Bench scale tests conducted by ADA suggested that most of the corona discharge were at the ends of the electrodes which are outside the usable portion of the ESP. The electrodes were replaced with 1/8" round wires were installed prior to the LMF5-H test. The results measured after the 1/8" wires were installed were the best recorded for the Rosebud coal, with emissions of 0.018 and 0.001 lb/MBtu, well under NSPS levels.

Pollution Control - NO_x

During the LMF5-F test, variations were conducted beginning with small quantities of potassium and increasing with time to eliminate the effect of free carbonate. Toward the end of the test, the effect of stoichiometry on NO_x concentration was studied. NO_x levels were generally higher during the entire test than were observed using a higher sulfur coal. Upon shutdown, water leaks were evident and could have contributed to a higher cooling rate of the gas which also would lead to higher NO_x levels. Table 4 shows the NO_x emissions during the scheduled stoichiometry variation during the prior LMF5-E test.

Table 4. Effect of Stoichiometry on NO_x Levels During LMF5-E

Thermal Input (MW)	Primary Stoichiometry	NO_x, Lb/MBtu
17.0	0.87	0.19
18.5	0.97	0.80
18.5	0.92	0.26
19.0	0.82	0.16
19.0	0.87	0.18

Tests during LMF5-G showed only a minor effect of thermal input on NO_x levels with a primary stoichiometry between about 0.8 and 0.87.

Additions of potassium carbonate above a K_2/S molar ratio of about 1.5 continued to eliminate sulfur dioxide. Measurements also confirmed the reaction between potassium and sulfur continues to occur downstream of the secondary combustor outlet instrument and the baghouse/ESP inlet, as shown in Figure 10.

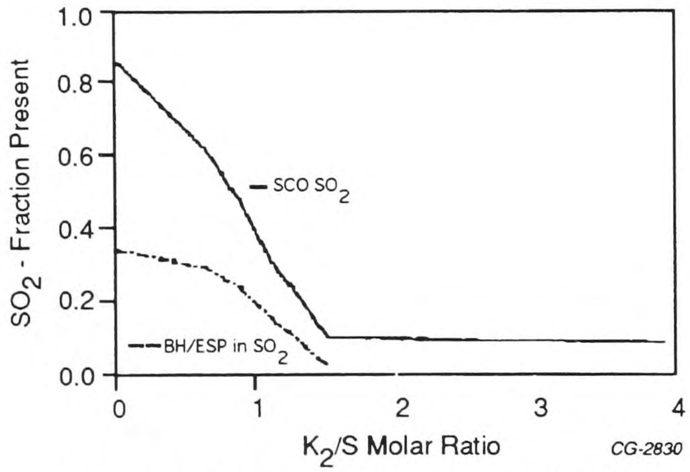


Figure 10. SO_2 as a Function of K_2/S (LMF5-F)

ASH DEPOSITION

This POC test series has two significant differences from the Illinois coal tests that may influence ash deposition. First, the Rosebud coal ash composition is significantly different from the Illinois coal ash. Second, the higher potassium to sulfur ratios result in a large excess of potassium carbonate, which has significantly different characteristics that potassium sulfate. The second difference is probably of more importance in the relatively short tests run in the low mass flow train. In the very long exposures of thousands of hours of continuous operation expected in commercial boilers, the coal ash composition may play a more important role than in the LMF tests. This is in part because of the generally slow reactions involving solids.

The results of the Rosebud tests to date have resulted in some observations. First is that the characteristics of the deposits are significantly different in appearance and composition. One physical difference is the characteristic blue color of the deposits. A significant amount of work has gone into identifying the reason for this color, but no firm conclusions can be drawn at this time. We do not believe it to be important in affecting properties that influence ash deposition. This topic is discussed in more detail below. Second is that the deposits were relatively friable compared to Illinois coal/ash deposits at higher deposit temperatures. Sootblowers were effective in maintaining deposition equilibrium throughout the SHTM, even through 'quiet periods' were requested by B&W when sootblower operation was suspended. . Deposit removal was also successfully controlled using a computer program to control operation of the sootblowers.

Ash deposition has been relatively consistent and well controlled during the entire period when Rosebud Coals were fired. Figure 11 illustrates that gas temperatures were maintained at the desired levels during the nearly 300-hour LMF5-F test. Results for the other tests were similar. Furthermore, as shown in Figure 12, the overall gas pressure drop through the SHTM was stable through this test, indicating that no significant accumulation of deposits occurred. Representative deposits from TS1 and TS3 are shown in Figures 13 & 14.

The distinctive blue deposits were observed during the first tests with Rosebud coal. While it is recognized that very small quantities of impurities can produce very strong colors, an effort was made to attempt to identify the material causing the blue color. There was some concern that one possible compound that might be responsible for the blue color is formed under reducing conditions. However, this seemed unlikely since conditions downstream of the secondary combustor are oxidizing, as confirmed by multiple CO_2 and O_2 analyses. Analyses of the deposits confirm this. Several analyses were made to determine the reason for the color and the state of oxidation of the compounds in the deposit. X-ray diffraction analyses made by Oneida Research Services, Inc. indicated the major crystalline compound to be $K_2CO_3 \cdot 1.5\ H_2O$. (Potassium Carbonate, trihydrate). No minor compounds were identified. From this it is concluded that the color is produced by a trace element/compound that is not detectable by X-ray diffraction analysis.

Calculations indicated that there was 1.35% excess carbonate above that required to tie up the

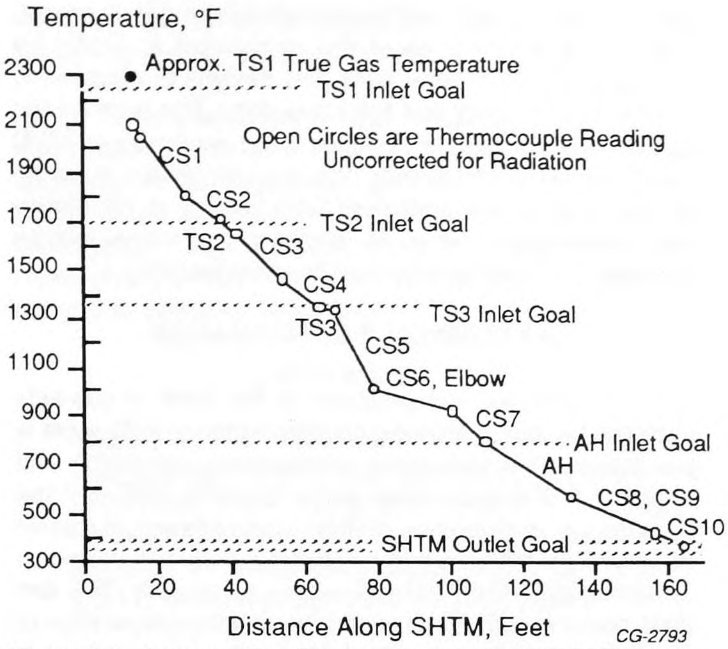
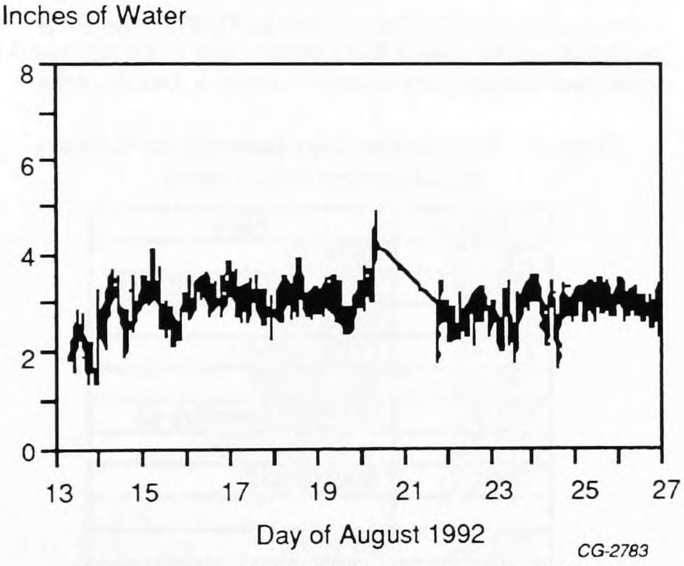


Figure 11. Average Gas Tempeatures in the SHTM During LMF5-F



Figue 12. Overall SHTM Pressure Drop, LMF5-F

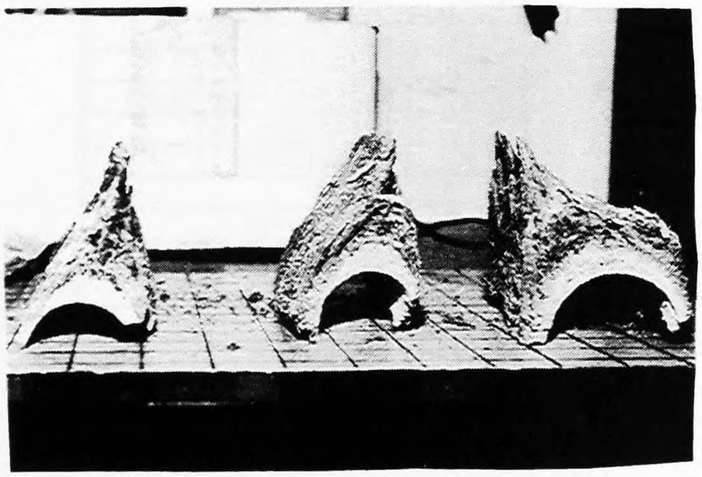


Figure 13. Ash Deposition TS1

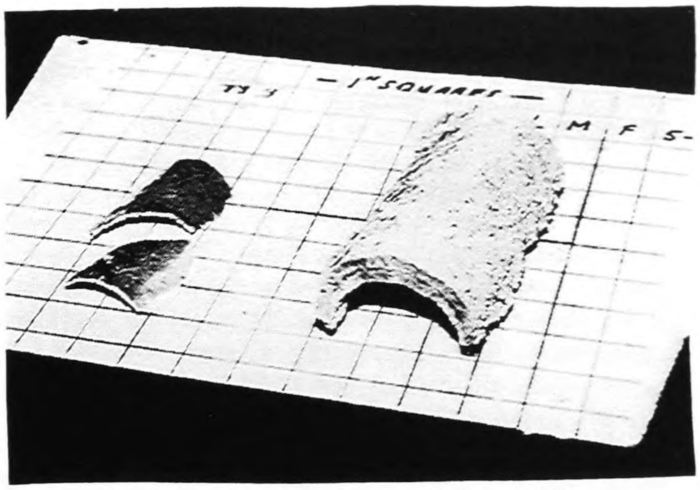


Figure 14. Ash Deposition TS3 and TS2

potassium not reacted with sulfur. In addition, analyses were performed on 5-stage cyclone samples. In these samples, it was observed that the blue color became more prominent as the particle size decreased. Potassium, sulfur and carbonate also increased as the size decreased. When samples were ashed at 1382°F (750°C) in an air (oxidizing) atmosphere, the blue color became more prominent. Addition of water to the ashed sample produced an immediate change of color to a pink/red. When the sample was dried, the color changed to white. Upon heating to 1382°F (750°C), the blue color returned. Thermogravimetric analyses of the samples indicated the blue color developed at about 1292°F (700°C) with no appreciable weight gain or loss. Based on these analyses, we conclude that the blue color was not caused by reducing conditions and that the blue color is not a result of hydration, since there was no significant moisture change when the color developed. Additional work will be necessary to determine the reason for the color.

Another significant effort related to ash deposition was that concerned with computer control of the sootblowing operation. This was accomplished using the gas temperature drop across each of three control zones for determining the blowing requirements in each zone. The gas temperature drop across each zone was used as an indicator of the extent of fouling since the last cleaning cycle (i.e., increased fouling = less heat removed from gases = lower differential between gas temperature entering and leaving that zone). By using running averages in determining the changes in gas temperature drops across a zone, the program is less sensitive to operating changes such as thermal input. The averages are then compared with set point references to determine when fouling has reduced the cooling efficiency to the point where sootblowing is desired. Set points are being empirically derived and improved as operating experience is gained. Since the purpose of sootblowing is to remove deposits and improve the heat transfer in a zone, blowing in one zone affects gas temperatures and heat absorption patterns in downstream zones. Effects such as these are being considered as operating experience and data are obtained.

Ash Deposition Modeling

A comprehensive 2-D real-time engineering model for ash deposition/heat transfer effects on site specific superheater tubes is being developed.[6] The site-specific capability will be very useful for predicting ash deposition in a future boiler retrofit application, or for optimizing design/operation details for a new, first-of-a-kind power-plant design. Variations with time in superheater deposit shape and heat-exchange performance will be predicted. Boiler design specifics, load, coal properties, boiler operational choices, and locally-entrained ash characteristics are input in terms of superheater tube diameter, steam temperature, flue-gas temperature, gas and particle velocity, gas and particle density, gas viscosity, multiple deposition time increments, particle diameter distributions, and dust loadings with elemental analyses for multiple narrow-range particle-diameter bins plus calculated viscosity for impacting particles. A coal ultimate analysis input is used to calculate flue gas composition and flue gas viscosity. Particle size distribution data from a five-stage cyclone measurement made near or downstream from the MHD secondary-superheater location, and elemental analyses of the stage-collected fly ash particles represent the major fuel-related input data.

Output of the UTSI model calculations includes two-dimensional deposit shape as a function of time, and location of impaction on the fireside surface as a function of impacting particle diameter. The calculated deposit shape (See Figure 15) can be compared directly with the actual superheater deposits generated during the combustion test that supplied the five-stage cyclone samples, or deposit shapes can be calculated for other site-specific locations (larger or smaller scale, as desired) assuming the same fly-ash particles were present at the other site. Initial comparisons were made during LMF5-H.

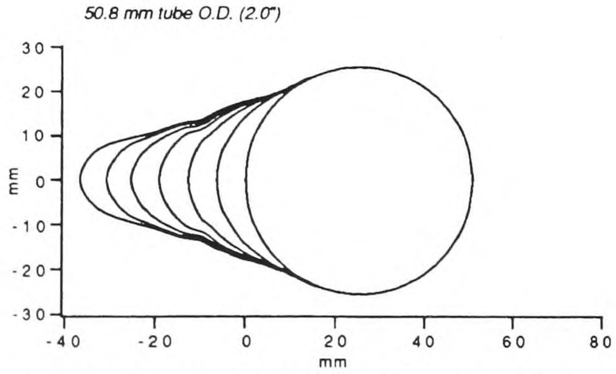


Figure 15. Calculated Deposition on 2-Inch Tube

The currently functional inertial-impaction module is one of several mass transfer mechanisms to be included in the UTSI model currently under development. The site-specific nature of the calculation is useful for scaling test data to other sizes and designs of equipment, and for relating pilot and full-scale data. The engineering calculations are being developed to be applicable to MHD conditions which frequently can include molten surfaces on deposits on a superheater tube located in the higher gas temperature zones. In addition, the model will be applicable to conventional coal-fired equipment.

MATERIALS PERFORMANCE

Activities and progress in the area of gas-side superheater and ITAH tube corrosion during 1992 were in two areas. One was in the preparation, installation and testing of SHTM test section tubes for LMF5 POC, and the preparation and testing of high temperature corrosion probes. The other was in the examination and corrosion evaluation of LMF4 POC test section tubes with 1500 and 2000 hours accumulated exposure, and the preparation of a report of the findings. The latter work is summarized in another paper being given at this meeting.[5]

The three test sections were installed at the beginning of the LMF5 POC tests. The materials used in these test sections are shown in Table 5, below. After LMF5-F, one-foot sections were removed for evaluation,

Table 5. Test Section Tube Materials for Montana Rosebud Coal POC Testing

Tube #	Alloy
TS1-1C	556/316
TS1-2C	RA85H/HR-160/253MA
TS1-3C	HR3C/347
TS1-4C	CR30A/304H
TS1-5C	310/IN 690
TS1-6C	CR35A/Tempalloy 43
TS1-7C	cr-800H/cr-T9
TS1-8C	MA956/347
TS2-1C	556/316
TS2-2C	RA85H/HR-160/253MA
TS2-3C	HR3C/347
TS2-4C	CR30A/304H
TS2-5C	310/IN 690
TS2-6C	CR35A/Tempalloy A3
TS2-7C	cr-800H/cr-T9
TS2-8C	MA956/347
TS3-1C	316/SA192
TS3-2C	347/T11
TS3-3C	T22
TS3-4C	T9
TS3-5C	T9
TS3-6C	T22
TS3-7C	347/T11
TS3-8C	304H/SA192

following 639 hours of exposure. Measurements are continuing and will be reported later.

The evaluation of high temperature materials is also continuing. Thermal shock continues to be a problem for many of the materials used because of the rapid temperature changes that occur when coal flow is interrupted. The Lanxide silicon carbide particulate reinforced alumina tubes continue to perform well with respect to corrosion resistance.

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