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**Advanced Coal-Fueled Industrial Cogeneration
Gas Turbine System
Hot End Simulation Rig**

Topical Report

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**For
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Office of Fossil Energy
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INTRODUCTION

This Hot End Simulation Rig (HESR) was an integral part of the overall Solar/METC program chartered to prove the technical, economic, and environmental feasibility of a coal-fueled gas turbine, for cogeneration applications. The program was to culminate in a test of a Solar Centaur Type H engine system operated on coal slurry fuel throughout the engine design operating range. This particular activity was designed to verify the performance of the Centaur Type H engine hot section materials in a coal-fired environment varying the amounts of alkali, ash, and sulfur in the coal to assess the material corrosion.

Success in the program was dependent upon the satisfactory resolution of several key issues. Included was the control of hot end corrosion and erosion, necessary to ensure adequate operating life. The Hot End Simulation Rig addressed this important issue by exposing currently used hot section turbine alloys, alternate alloys, and commercially available advanced protective coating systems to a representative coal-fueled environment at turbine inlet temperatures typical of Solar's Centaur Type H. Turbine hot end components which would experience material degradation include the transition duct from the combustor outlet to the turbine inlet, the shroud, nozzles, and blades. A ceramic candle filter vessel was included in the system as the particulate removal device for the HESR. In addition to turbine material testing, the candle material was exposed and evaluated. Long-term testing was intended to sufficiently characterize the performance of these materials for the turbine.

SYSTEM DESCRIPTION

The design of the HESR had to achieve several objectives. Most critical were size of the rig and the material environment. Performing this study in an engine would prove too costly, therefore, the rig design was small to minimize long-term test costs. The gas environment for the materials had to match that of the full-scale, coal-fueled engine. Exhaust gas temperature, pressure, and composition would have to be repeated in the small-scale rig.

The Hot End Simulation Rig consisted of three major components: a two-stage slagging combustor (TSSC), a filter vessel housing a single ceramic candle filter, and a candidate material sample section. The test hardware configuration is shown in Figure 1. The small scale TSSC design is based on a similar combustor designed, fabricated, and tested under the DOE/METC components screening program.

Combustor

The TSSC consisted of a slagging primary zone, a single dual fuel injector, and a radial air injection secondary zone, illustrated in Figure 2. In sizing the combustor, the primary zone residence time was maintained at the same level as that of the components screening rig. This necessitated a decrease in the combustor loading since residence time specifications required an increase in combustor chamber volume. The primary and secondary zones designs were based upon char and coal burnout times, adiabatic flame

PD90270M

Figure 1. Schematic of Test Hardware Configuration

Figure 2. HESR Primary and Secondary Combustion Zones

temperature, and an equivalence ratio of 1.3 that were determined from testing of the larger combustor. In order to minimize fuel costs to economically complete testing, a 1-2 gallons/hour flow rate was selected and was a major consideration in component design.

Combustor - Primary Zone

The primary zone was cast of high temperature, slag resistant, refractory to operate at 2000-2600°F. The primary combustor was operated under fuel-rich conditions to minimize the conversion of fuel bound nitrogen into NO_x and match operating conditions of the full-scale engine combustor to simulate exhaust constituent characteristics. Fuel, primary air, and air assist were introduced through a single, dual-fuel injector to produce a narrow-angled jet of a well atomized fuel/air mixture. The fuel tube was common to both diesel, used to preheat the rig, and CWM. Much development work was accomplished to achieve a viable fuel injector which would yield good atomization and not plug with coal. The final injector version alleviated the plugging problem and achieved over 70 hours of operation on CWM. This injector design featured an air assist annulus to aid in atomization and to shield the fuel tube, down to the tip, from the high temperature primary zone to prevent plugging. Also in the fuel line were small mesh fuel strainers to protect the injector from debris and other matter which could plug the injector. Due to the small mesh size, a coal-water slurry without a stabilizer was used. Stabilizer affects the suspension characteristics of the slurry. When a fuel including stabilizer was used, the fuel strainers plugged with a gummy matter which inhibited fuel flow.

Injector

Several iterations of injectors were fabricated and tested. Variations included fuel tube size, transfiguration of air injection points, the use of water cooling, and the use of air assist. The final injector version used an air assist annulus to shield the fuel tube from primary zone heat and logged over 70 hours of effective operation on CWM.

Version 1 was a basic dual-fuel injector with a centered fuel tube which was encompassed by a primary air annulus. This injector burned up upon initial testing. Version 2 had a air purge line added to it. Plugging of CWM in the injector resulted. Modification 3 incorporated a water-cooled fuel tube to shield it from high primary zone temperatures. Several tests were performed with no plugging of the fuel tube. During Hot End Rig testing, plugging occurred due to a rapid variation of the fuel flow rate. It was concluded, through additional atmospheric tests, that any disruption in the fuel flow would cause plugging of the injector at its smallest constriction at the tip. Injector version 4a recessed the fuel injector back into the refractory to decrease exposure of the tip to hot primary zone temperatures. In addition, the fuel tube was enlarged to guard against plugging. However, after several tests, the injector did plug, even with a water purge manifold installed to periodically clean the fuel tube during CWM flow.

Injector version 5, illustrated in Figure 3, incorporated an air assist annulus around the fuel tube mainly to shield the tube down to the tip of the injector from the primary zone temperatures, and also to aid in atomization. Although all previous injector modifications

Figure 3. HESR Injector Version 5

yielded good atomization results, version 5 produced exceptional mean drop sizes of 12 microns and 90% of the drops less than 50 microns. Verification of the injector was done using CWM Batch 'R' which did not contain a stabilizer and, therefore, did not block the CWM feed system extending injector life.

Combustor - Secondary Zone

In the refractory-lined secondary zone, combustion was completed as CO, H₂, and unburned hydrocarbons from the primary zone were burned, and process temperature was reduced from 2700°F to turbine inlet gas temperatures of 1850-1900°F, typical of Solar's Centaur Type H. Maximizing the mixing in the secondary zone, six equally spaced, radial air jets collided with the primary zone exhaust. Mixing of the secondary air and the primary zone products was designed to occur as rapidly as possible to minimize the time at high temperatures associated with stoichiometric conditions which produce thermal NO_x from the nitrogen in the air. The collision of the two flows resulted in a rapid mixing, suppressing NO_x formation.

Filter Vessel

The combustion gases from the secondary zone combustor were filtered prior to the material sample section to eliminate the corrosive effects of particulate deposition on the samples. A refractory-lined filter vessel, located downstream of the secondary combustor and upstream of the sample section, housed a single ceramic candle filter. The candle was suspended from a tubesheet and compliant gaskets were used to provide a mount and dust seal. The gas, typically at 1850-1900°F, entered the filter vessel towards the

top of the vessel and was deflected by a metal shroud constructed of RA-330. This shroud protected the candle from direct impingement of particulate.

The filter candle was constructed from a silicon carbide material imbedded in a clay binder. A thin outer layer had the smallest pores and finest grains permitting high collection efficiencies at fairly modest pressure drops. The innermost layer was comprised of fairly large pores to minimize pressure losses. The accumulating dust cake was dislodged from the outer layer of the candle by a reverse jet of high pressure air. Typically, a one-second pulse of air was used to periodically remove the dust. A candle material change was implemented during testing and is discussed in the Test Results section.

Material Sample Section

The sample section housing was refractory-lined and located downstream of the filter vessel. It was designed for exhaust gases at 1850-1900°F to flow over the material specimens which were situated in a removable assembly shown in Figure 4. Cooling air was metered to the materials samples to simulate the material temperatures in subsequent turbine stages. Figure 5 illustrates how the air was introduced to the paired specimens. During shakedown tests, it was found necessary to install heaters just upstream of the material section to bring the exhaust gas up to design temperature. This was necessary due to the unreasonable fuel cost and heat-up time for the sample section to reach equilibrium at design temperatures.

Figure 4. Material Sample Section Assembly

Figure 5. Cooling Air to Material Test Specimens to Simulate Turbine Stages

Cast materials were procured in the form of 0.375 in diameter solid bars in lengths ranging from 3.5-4.0 inches, whereas wrought materials were obtained as 0.375-0.5 inch diameter bar stock. The bars were reduced to 0.375 inch diameter when necessary, cut to lengths ranging from 3.0-3.5 inches and subsequently hollowed-out by EDM methods. The wall thickness of the hollow bars thus obtained, varied between (0.060-0.080 inches). The test specimens were welded to stainless steel tubes, which carried the cooling air necessary to obtain the target test material temperatures.

Materials selected for initial testing are listed in Table 1. A schematic of the positioning of the materials and the temperature distribution is shown in Figure 6. All of these materials, with the exception of Haynes Alloy 230, DS CM247LC, and CMSX-2, are currently used in the Centaur Type-H engine. Haynes Alloy 230 represented a material with higher corrosion and temperature capability than Hastelloy X, and could be used in uncoated applications, either as claddings or fabricated airfoils, as well as combustor liners and transition ducts. DS CM247LC and CMSX-2 are columnar grained and single crystal blade alloys respectively, with higher temperature capability than equiaxed blade alloys such as IN-738LC and IN-792(5A), and could be used without internal blade cooling.

Table 1. Sample Materials Selected

Alloy	Type	Typical Material Operating Temperature Range (°F)	Centaur H Engine Application
Haynes 230	Ni-base sheet superalloy	to 2200	Not in use
Hastelloy X	Ni-base sheet superalloy	1200-1900	Transition duct/ combustor liner
FS-414	Cast Co-base superalloy	1200-1700	Turbine nozzles
IN-738LC	Cast Ni-base superalloy	1100-1600	Turbine blades
CM247LC	Ni-base columnar grain superalloy	to 1700	Not in use
CMSX-2	Ni-base single crystal superalloy	to 1750	Not in use
IN-792(5A)	Cast Ni-base superalloy	800-1400	Turbine blades
N-155	Cast Fe-Ni superalloys	800-1250	Turbine nozzles
V-57	Wrought Fe-Ni superalloy	800-1200	Turbine discs

Figure 6. Material Positioning and Temperature Distribution

Coating systems selected for testing are listed in Table 2. These included modified pack diffusion aluminide coatings (RT-22A, RT-44, and SS82B), a slurry-applied aluminide coating (Sermalloy J), MCrAlY overlay coating where M=Ni and/or Co (RT-31 and RT-119), a thermal barrier coating (RT-31/RT-33), and a gas phase coating RT-57. Table 3 lists the turbine engine material, coating system if applicable, and test temperatures of the 18 specimens undergoing the test.

Table 2. Coating Systems Selected

Coating Type	Designation	Process	Supplier
Pt-Aluminide	RT-22A	Plating + pack cementation	Chromalloy
Pt,Rh-Aluminide	RT-44	Plating + pack cementation	Chromalloy
Pt,Cr-Aluminide	SS82B	Plating + pack cementation	T.C.C.
Sl-Aoluminide	Sermalloy J	Slurry	Sermatech
CoNiCrAlY	RT-31	EB PVD	Chromalloy
CoNiCrAlY Bond coat + Yttria Stabilized Zirconia	RT-31/RT-33	EB PVD	Chromalloy
High-Cr CoCrAlYSi	RT-119	LPPS	Chromalloy
Chromium	RT-57	Gas phase	Chromalloy

To minimize heat losses from the exhaust gas, supplementary heat input was provided by coiled, Inconel sheathed heating elements mounted inside the 4 inch duct on the refractory walls at the exit of the filter vessel. Several problems were encountered during use of these elements. Included was corrosion of the outer sheath due to a leak in the filter vessel causing ash to leak downstream of the filter, and exposure of the electrical wires and subsequently heater failure. Another cause of breakdown was over-temperature of the coils due to a faulty rheostat. Another concept was incorporated to supply the supplemental heat necessary. This new strategy employed the use of a natural gas and air mixture impinging on a baffle upstream of the material samples and igniting with the use of a spark plug. Several attempts were made to implement this method, to no avail. A modified torch nozzle was then fabricated and installed upstream of the material samples. Internal ignition of the natural gas was not possible. Diesel was successfully used as the fuel, although there existed a risk of depositing unburned fuel onto the material samples. The diesel was slowly leaned out over the course of a run as filter vessel exhaust temperatures eventually reached equilibrium.

**Table 3. Turbine Material With Associated Coating Systems
and Test Temperatures**

Material	Coating	Test Temperature F (°C)
Hastelloy X	RT-31/RT-33	1800 (982)
Haynes Alloy 230	RT-31/RT-33	1800 (982)
CMSX-2	---	1700 (927)
DS CM247LC	---	1700 (927)
FS-414	RT-31	1700 (927)
FS-414	RTJ-44	1700 (927)
FS-414	RT-119	1600 (871)
FS-414	Sermalloy J	1600 (871)
IN-738LC	RT-31	1600 (871)
IN-738LC	---	1600 (871)
IN-738LC	RT-22	1500 (816)
IN-738LC	Seramalloy J	1500 (816)
IN-792(5A)	RT-119	1300 (704)
IN-792(5A)	SS82B	1300 (704)
IN-792(5A)	RT-57	1100 (593)
V-57	---	1100 (593)
N-155	RT-119	1200 (649)
N-155	Sermalloy J	1200 (649)

SYSTEM TESTS

Test Procedure

Thousand hour tests were planned to evaluate material corrosion as a function of coal fuel alkali, ash, and sulfur content. Testing would determine which coal slurry is most economical and which grade of coal would be most suitable to meet Solar's maximum allowable hot end corrosion criterion, which varies from one hot end component to another. Acceptable rates of material loss vary from <0.0013 cm/1000 hour (0.0005 inch/1000 hour) for cooled, rotating components to approximately 0.100 cm/1000 hour (0.002 inch/1000 hour) for less critical, heavy section static parts.

A medium sulfur and ash level, 300 ppm alkali content fuel was selected for the first 1000 hour test. Table 4 shows characteristics of Batch 'R' which was to be used in the first 1000 hour test. Based upon prior testing, Batch 'R' was selected for its transportation and non-plugging properties. In order to reduce unnecessary testing, inspection of the material samples was to be performed at 100-250 hour intervals. If the majority of the materials displayed unacceptable corrosion levels, the test would be terminated and a new fuel would be chosen for another series of 1000 hour testing. The fuel grade selection was to proceed as shown in Figure 7. No doping or mixing of the fuel was necessary to achieve the alkali levels; these specifications were met with various cleaning methods. The coal loading in the fuel was 55 percent and the particle size was 45 microns.

The hot end evaluation was to culminate in a long-term, 5000 hour test once materials and fuel grade had been determined through the 1000 hour tests. A minimum of 5000 hours would be necessary to yield meaningful materials evaluation results since many materials exhibit non-linear corrosion rates. Long-term testing would have yielded quantitative results where as the 1000 hour, preliminary tests resulted in qualitative, comparative conclusions.

Analysis Procedure

The test specimens were visually inspected during each shutdown period. If a test material displayed unacceptable degradation, it was to be replaced. Evaluations on coated and uncoated test specimens were to include visual characterizations, chemical analysis of surface contaminants, and metallographic sectioning for light microscope and SEM characterization of material loss. Surface recession rates were defined by examining cross sections, and characterization of scales and reaction products were to

Figure 7. Fuel Selection Flow Chart

Table 4. Characteristics of Coal Slurry Fuel Batch 'R'

CWM	R	
Coal Source	Kentucky 4A	
Coal Content (wt%)	54.34	
Ash Content	2.07	
Slurry Viscosity (cp)		
@ 100/sec	150	
@ 1000/sec	190	
Slurry LHV (Btu/lb)	7855	
Coal Characteristics		
Proximate Analysis (wt%)		
Ash	3.9	
Volatiles	34.82	
Fixed Carbon	61.28	
Ultimate Analysis (wt%)		
Carbon	74.98	
Oxygen	5.56	
Hydrogen	5.56	
Nitrogen	1.78	
Sulfur	0.92	
Ash Composition (wt%)		
SiO ₂	46.49	
Al ₂ O ₃	28.31	
Fe ₂ O ₃	12.00	
CaO	4.16	
MgO	0.79	
Na ₂ O	1.20	
K ₂ O	0.96	
TiO ₂	1.09	
MnO ₂	-	
P ₂ O ₅	0.16	
Ash Fusion Temperature (°F)	<u>Oxidizing</u>	<u>Reducing</u>
Initial Deformation	2672	2387
Softening	2694	2419
Hemispherical	+2700	2467
Fluid	+2700	2651

be performed by X-ray microanalysis (EDS) methods. Localized effects due to sticking of ash and slag particles were to be characterized and mechanisms of material degradation (Type I and Type II hot corrosion, oxidation, erosion) defined. Results would have been compared to allowable rates of material loss for the various components. With the limited testing and exposure time, no unacceptable deterioration was observed.

Results

The following is a summary of all HESR tests. After shakedown, much development work was performed to achieve a viable fuel injector which would yield good atomization and not plug with coal slurry. With this accomplished, tests were performed and modifications made to improve rig reliability for endurance testing of the material samples. Total test time burning CWM accumulated to approximately 164 hours. A chart summary of all HESR tests is found in Table 5. Although the endurance objective was not fulfilled, only minor modifications would be needed to ready the HESR for long-term testing.

Tests HESR-1 through HESR-7 mainly involved system checks and the demonstration of a viable fuel injector. Significant modifications were made to the fuel tube and the cooling of it. A workable injector resulted in version 5. This injector incorporated an air assist annulus around the fuel tube shielding it down to the tip from the high primary zone temperatures. The additional air also resulted in better atomization.

HESR-8 tested injector version 5 and AMAX Batch 'R' fuel. The combustor operated smoothly at 94 psig with the CWM flow rate set at 20 lb/hr. The test was voluntarily terminated after running a total of 5 hours on CWM, burning 98.6 lbs. Having successfully completed HESR-8, emissions data would be collected in HESR-9 using the same injector and batch fuel. Again, the combustor ran smoothly at 94 psig and an inlet air temperature of 580°F. The equivalence ratio in the primary zone was relatively constant at 1.34. The combustor outlet temperature peaked at 1920°F. As shown in Table 6, the emissions data are exceptional with low NO_x, CO, and UHC. Plugging of the gaseous emissions sampling probe reduced the number of CWM emissions points, however, the data gathered surpassed all requirements. Post test inspection of the combustor revealed slag freezing around the slag tap hole inhibiting molten slag to flow into the slag pit. Installation of torches directed at the slag tap hole were expected to resolve this problem. Examination of the secondary zone showed no slag escape or plugging.

Due to a change in personnel, a 12 hour injector endurance run was performed without the filter vessel in line to reinforce the viability to version 5 and gain operational experience. During CWM operation, the primary zone equivalence ratio was fairly constant at 1.32 and exhaust temperatures were 1100°F, typically. At the 11.5 hour mark the injector plugged momentarily, stopping the CWM flow, but was quickly cleared of fuel and the normal diesel shutdown procedure was followed. Total time on CWM was 11.5 hours burning 260.0 pounds. Due to the successful results achieved using injector version 5 with CWM Batch 'R', Amax was contacted to supply slurry fuel with characteristics similar to Batch 'R' for future HESR tests. Batch 'R' characteristics are shown in Table 4. Upon teardown of the rig, inspection revealed some slag accumulation on and around the impactor. Also, a measurable amount of bottom ash was observed in the slag pit. This material amounted to about 2.5 lbs and was quite light having a bulk

Table 5. Summary of Hot End Simulation Rig Testing

Test No.	Objective	CWM Batch	Hours on CWM	P _{in} (psig)	T _{exhaust} (°F)	φ _{primary} (typ)
1	Initial check-out run	'M'	4 DF#2	80	1580	1.25
2	Teseting of injector ver. 2	'M'	52 DF#2	93	1560	1.21
3	Testing of injector ver. 3	'M'	2 CWM	83	1622	1.05
4	Testing of injector ver. 4A	'M'	4 CWM	67	1548	1.05
5	Testing of injector ver. 4A w/lower fuel flow rate	'M'	25.5 DF#2	110	1404	0.79
6	Evaluation of injector ver. 4A	'M'	3:00	79	1700 ²	1.16
7	Evaluation of injector ver. 4A	'M'	0:15	82	N/A	N/A
8	Evaluation of injector ver. 5	'R'	5:00	85	1733	1.18
9	Evaluation of injector ver. 5	'R'	6:00	90	1820	1:20
11 ¹	Injector endurance test	'R'	11:30	85	1100	1:21
12	Candle test	'R'	4:00	83	600 ³	1:16
13	Test higher candle purge pressures	'R'	3:33	83	800	1:22
14	Retest of No. 13	'R'	2:09	82	860	1:23
15	Evaluation of modified purge system	'R'	4:00	83	900	1.35
16	Evaluation of sample section heating	'R'	19:05	83	1300	1:25
¹ Test No. 10 terminated due to data acquisition system difficulties. ² Exhaust temperatures measured downstream of secondary zone. ³ Filter vessel and material sample section in line. Exhaust temperature measured downstream of sample section.						

Table 5. Summary of Hot End Simulation Rig Testing (Contd)

Test No.	Objective	CWM Batch	Hours on CWM	P _{in} (psig)	T _{material sample section} (°F)	φ _{primary} (typ)
17	Evaluate RA-330 candle filter shroud. Evaluate interam gasket in candle mount	'R'	4:12	82	N/A	1.25
18	Extended evaluation of interam mount	'R'	6:08	76	N/A	1.25
19	Assess heat coils in matelal sample section	'R'	7:43	87	1187	1.23
20	Assess modified cup/candle mount assembly	'R'	4:09	87	N/A	1.20
21	Evaluate ceramic wool in cup assembly	'R'	4:09	87	N/A	1.15
22	Evaluate ceramic wool in cup assembly	'R'	3:58	85	N/A	1.15
23	100 hour material evaluation	'R'	5:00	83	949 ¹	1.19
24	100 hour material evaluation	'R'	13:30	86	1292 ¹	1.22
25	Evaluate conical primary zonea nd impactor sectoin	'R'	4:01	82	762	1.22
26	Assess modified sample section heating	'R'	3:20	80	772	1.23
27	Assess modified sample section heating	'R'	3:27	80	816 ²	1.19
28	Assess modified sample section heating	'R'	4:00	81	816 ²	1.19
					T _{exhaust} (°F)	
29	Verify slag conical separator and natural gas torch	'R'	5:30	80	700	1.20
30	Vary CWM fuel flow and ___/sec air split	'R'	4:30	82	1488	1.19
31	Verify fibrosis candle in filter vessel	'R'	7:30	80	1800	1.20
32	Expose material specimens to exhasut at design conditions	R-8	4:00	80	1316 premature shutdown	1.20
33		R-8	14	85	1753	1.20

¹Temperatures measured with electric heaters installed.
²Recorded temperatures were measured with torch installed prior to material sample section. however, temperatuarees were observed to read 1600°F+ when torch was ignited.

Table 6. HESR-9 Emissions Data

Fuel	Batch 'R'
T_{in} (°F)	580
P_{in} (psig)	94
Φ_{primary}	1.34
T_{outlet} (°F)	1705
Emissions @ 15% O₂ ppmv, (lbs/mmBtu)	
NO_x	30.98 (0.1390)
CO	1.83 (0.0047)
UHC	5.96 (0.0070)
SO₂	Not measured
Slag Rejection	Not measured
Carbon Conversion	Not measured

density of only 11.5 lbs/cu ft. Analytical data indicate that the material was 47.2% carbon and 52.8% ash. The 2.5 lbs of material amounted to about one percent of the entire CWM fed to the system, or roughly 2 percent of the fuel on a dry basis. Because of the extremely low bulk density of the material, it is possible that removal of the material during long duration runs will be required.

More development work was accomplished in order to improve rig reliability for future long term tests. A torch was installed to supply periodic heat to the impactor area to discourage slag accumulation there. Continuous operation of the torch was not planned as additional combustion air would upset the primary zone equivalence ratio. Thermocouples were added to the secondary zone exhaust leg. During previous tests, this leg developed a hot spot. The additional thermocouples indicated if this section was being unduly heated.

During HESR-12, the rig was operated for 4 hours with a single Schumacher dia-Schumalith candle filter in-line. After the run, the candle was removed for inspection. The dust loading in the Hot End Rig is fairly low as there is no sorbent injection system. As a result, the load on the candle filter is significantly reduced and purging is not often required. In fact, the pressure drop measured across the tube sheet did not exceed 2 psid for the entire test. Purging was typically initiated when the differential pressure has reached about 3 psid. Nonetheless, cleaning of the candle was tested with purge pressures of up to 200 psig (combustor pressure was about 90 psig throughout the test). At these pressures, there was no apparent change in the differential pressure across the tubesheet. When the candle was removed, a thin layer of dust was observed on most of the candle. This was removed readily from the candle and was analyzed. Moreover,

dust was observed at the bottom of the filter vessel. Apparently, some cleaning of the candle did take place. The incomplete cleaning of the filter, however, was most likely the result of purge pressures that were too low.

The next series of tests, HESR-13 AND -14, were completed to determine if higher pulse pressures would be adequate in purging a single candle. HESR-14 was run for two hours after which time it became apparent that higher purge pressures were not effective in cleaning the candle. No change in differential pressure was observed when pulsing, regardless of the purge pressure. However, all candle filter tests have operated as expected with respect to filtration.

Next, HESR-15 was operated for 4 hours to verify a modified purge system incorporating a 0.75 inch purge tube and an increased pulse duration from 0.1 to 0.5 seconds. The system worked as designed even at low purge gas pressures of 150 psig. The drop in differential pressure across the candle was sufficient such that no further increase in pulse pressure was required. The modified purge system was successful.

An area of concern, especially for long term runs, involved the impactor spool and the slag pit. Temperatures measured in these regions had been consistently too cool to allow the slag to flow, and as a result slag had filled the impactor area and, on occasion, part of the primary zone. The installation of torches directed at the impactor area did not resolve the matter. In order to combat the problem, a new impactor spool piece which incorporated several insulating and refractory materials was investigated. Cones of Kaocrete HPM 90, Kaolite 2800, and Kaolite 2300 made up the impactor area. The concept was to keep the slag tap hole hot enough to maintain slag in the molten form to flow down into the slag pit. To further enhance the heat supplied, impactor or slag pit refractory cast heating elements were also investigated, but not incorporated.

The material sample section was instrumented with thermocouples and installed in the rig. Since previous 4 hour tests showed that the measured sample section inlet temperatures did not exceed 1100°F, an extended run was performed. It was thought that an extended heat-up on diesel would bring the sample section up to the design temperature of 1900°F, which is representative of the DCFT exhaust gas.

In HESR-16, the rig was operated over 24 hours on diesel and coal water slurry. A total of 422 lbs. of CWM was burned over a period of 19 hours. Sample section temperatures increased throughout the run as the gas inlet temperature to the sample section reached 1500°F. Inlet filter vessel temperatures reached 1900°F, but downstream sections were much cooler. These temperatures over time are shown in Figure 8. The two 1100°F and two 1200°F coupons in the material sample section required metered cooling air to obtain their setpoints. The 1300°F coupons were close to their setpoint although cooling air was not necessary. Temperature controllers and proportional solenoid valves were obtained to accurately control the temperature of the material coupons.

Figure 8. HESR-16 Temperatures of Filter Vessel Inlet, Candle, and Sample Section vs. Time

Candle performance was of great interest during this run. The candle filter saw gradually increasing temperatures throughout the run. The peak temperature at the filter vessel inlet was recorded at 1970°F, although temperatures in the downstream, or clean, side of the candle reached a peak of 1776°F. Purging cycles were effective in cleaning the filter initially, yet ineffective towards the end of the run. The differential pressure across the candle filter reached about 5 psid; at this point the candle became very difficult to clean. Subsequently, a shutdown procedure was initiated. It is not clear if the candle was blinding or if reentrainment was a contributing factor. The nature of the dust collected and the fact that the candle appeared fairly clean indicated that gradual blinding was more likely the cause. During the run, the backside of the candle was observed through a window and appeared clean. However, the side near the inlet piping had an accumulation of ash which did not come off with purging, even at pulse pressures of up to 290 psig.

Upon post-test inspection of the rig, very little accumulation of slag was observed in the secondary combustor area. Particulate was collected from the bottom of the filter vessel. This particulate was comprised of a fairly cohesive dust which was purged from the candle during the earlier stages of the run. On top of this dust was observed additional particulate which had retained the shape of the candle, indicative of the very cohesive dust. These pieces were generally about an inch or so in length and very hard and glass-like.

Another area that required special attention was the exhaust section. The back pressure valve displayed an inordinate amount of corrosion presumably due to acid attack. During the run, it became necessary to control the pressure of the rig using two ball valves in conjunction with the back pressure valve. Unfortunately, the ball valves experienced the same corrosion. Since no sorbent was utilized, nearly all of the sulfur in the coal was converted to gaseous sulfur dioxide. The back pressure and ball valves were exposed to the gas below its dew point. This was resolved by implementing acid resistant materials at the appropriate locations in the system. Also, by reducing the amount of cooling water to the exhaust, and operating with the acid resistant components, the valve corrosion problem was resolved.

During post-test inspection of the rig after HESR-16, it was discovered that the impactor has slagged over and the slag had built up approximately one inch into the primary zone. Another primary zone was cast and installed. A new impactor section insert, the piece in which the impactor rests, was fabricated. Two inches of Ultracast 90 surrounded the impactor to protect it from corrosion and erosion, and the remaining seven inches were made of Kaolite 2300 to insulate the impactor area and enhance slag flow.

In evaluating HESR-16, it was concluded that additional heat input was required to economically achieve material sample section temperatures. The Hot End Rig could be operated for an extended period of time to reach target temperatures, but this would not have been feasible due to the added fuel and manpower expense. Therefore, the use of electric heaters was researched. It was discovered that few heating elements could withstand the high temperature, alkali environment. Silicon carbide heaters were investigated, however, due to the structure of the heaters, they could not be used or modified to use inside a pressure vessel. Therefore, the heater of choice was a, flexible, Inconel sheathed heater which could be coiled to fit inside the 4 inch duct prior to the sample section. A new spool piece to accommodate the heaters was also designed and fabricated.

A shroud of RA-330 was fabricated and welded to a spacer near the tubesheet at the inlet of the filter vessel near the exit of the secondary combustion zone. In earlier runs, solids built up selectively on the candle at the area closest to the gas inlet. A slag-like material or highly sticky ash formed on the side of the candle that sees the inlet gas stream, while the back side of the candle appeared clean. The shroud was placed in front of the candle, directly in the flow path, to inhibit candle blinding which was believed to have occurred during HESR-16, contributing to poor candle performance.

The objective of HESR-17 was to test the RA-330 shroud and a new candle mount system using Interam gasketing material. The combustor ran smoothly throughout the run. The short duration of the run combined with the low dust levels made it unnecessary to the purge the candle. The highest differential pressure for the candle was 0.28 psid. In post-test inspection, the candle appeared to have been protected by the shroud from the dust-laden inlet gas. Although the temperature in the filter vessel only reached 1248°F, the candle mount system appeared effective.

HESR-18 tested the new candle mount more rigorously during an extended run at a higher temperature. The combustor ran smoothly throughout the run, although post-test

inspection revealed that slag had accumulated in the primary zone and around the impactor. The candle mount system again appeared to be effective. No dust was observed downstream of the filter vessel.

HESR-19 was run to assess the heater coils. Heaters were instrumented with thermocouples and then coiled to fit inside the four inch duct. An oxidation resistant coating was applied to the heaters to inhibit corrosion/erosion and extend heater life, as the heater sheath was only Inconel. The rig ran very smoothly, with no difficulties encountered, at an equivalence ratio of 1.23 (typ), burning 178 lbs. of CWM. With the electric heaters installed in the duct prior to the sample materials, supplemental heat was added to boost the gas temperature to 1850°F. The run began with the heaters setpoint at 1200°F, which was slowly increased to 1850°F over time. About 8.5 hours into the run, with the setpoint at 1650°F for nearly an hour, no change in material temperature occurred, indicating a problem. With temperature and power controllers giving correct readings and signals, the only conclusion was that the heaters had failed. Since the material design temperatures could not be achieved in a reasonable time, a diesel shutdown procedure was initiated.

Upon teardown, the rig was inspected. Most promising was the impactor. It did not slag over, and part of the gap to the slag tap remained open. Although no slag was found in the slag pit, it was dripping down in shapes similar to a stalactite.

In the material sample section, the Inconel sheath on the heaters was melted at the critical hot/cold junction where the sheath material necks down to the outlet of the spool. It is believed that the refractory that covers the cold section of the heaters to seal them in the rig also covered the critical junction, creating a hot spot and eventually melting the sheath. Figure 9A. shows the heater coil installed in the spool piece. Figure 9B. shows the dusting of particulate on the heater after HESR-19. New heaters were ordered and a modified installation procedure was followed.

Also in the sample section, ash was found. Removal of the candle revealed the places where ash escaped. The filter vessel 'plug', which slides down into the filter vessel and to which the tubesheet and candle are attached, exposed several ash streams around it. The plug did not seal well in the vessel and left a small gap for ash leakby. Ash streams were also found on the candle mount itself.

The mount and plug were modified for HESR-20, which was run without the material samples installed. Again, the rig ran very smoothly at an equivalence ratio of 1.20, burning 90.5 lbs of CWM in 4 hours. To correct the dust leakage problems, a cup was fabricated from RA-330 to secure the candle and Interam gasketing material, which was suggested by Industrial Filter & Pump, in the new mount. The cup assembly was mounted flush with the tubesheet. Rather than weld the cup to the tubesheet, i.e., to prevent dust leakage, a refractory material was used to seal the gap. This method was judged superior as grinding off a weld would almost certainly lead to a broken candle. The filter vessel plug was wrapped in a blanket material which was held in place with nichrome wire. When the plug was placed inside the vessel, the insulating blanket created a seal around the plug stopping ash leakage. Upon removal of the candle from the filter vessel, no ash leakby was observed. However, after further inspection, the

Figure 9a. Heater Coll Prior to Material Samples

Figure 9b. Heater Coll with Dusting of Particulate

Interam gasket in the candle mount was excessively deteriorated such that it could not be run again, and another seal material would be necessary.

HESR-21 assessed another modified candle mount. In place of the Interam gasket, a ceramic blanket material was used in the same mount assembly which is illustrated in Figure 10. This material also has cushioning properties that permits the candle to have some flexibility. The run started in the usual manner with a six hour preheat period on diesel fuel, followed by four hours on CWM, burning a total of 96 lbs. of coal slurry fuel. The run concluded with a three hour period of diesel to facilitate slag flow into the pit. It was suspected that in previous runs the more rapid shutdown procedure was responsible for slag freezing around the impactor. Upon teardown of the rig, this modified procedure appeared to have lessened the problem; however, frozen slag deposits were still observed around the impactor. Having inspected the candle mount, it was discovered that the high temperature ceramic wool material used as a gasketing material had failed due to improper installation. The exposed material was located downstream of the filter vessel. It apparently blew out during the run.

The use of the ceramic wool gasketing material in the candle mount was tested again in HESR-22. The combustor ran well at an equivalence ratio of 1.15 (typ). A four hour run was performed burning 82 lbs of CWM. No difficulties were encountered during the run. Upon inspection of the rig, no ash was found in the material sample section, nor around the candle mount or filter vessel plug. The new mount system was successful.

At this point in testing, three methods of mounting a candle to a tubesheet had been analyzed. The first method was the so-called rigid-mount method where the candle is cemented into a cup with a refractory material. This formed a gas tight seal, but did not permit candle movement. Candles had failed with this type of mount, however, it was not

Figure 10 . Candle Filter Mount

clear whether the mount was part of the cause. The Industrial Filter & Pump method used an Interam gasketing material to provide the seal. Several tests in the Hot End Simulation Rig revealed that this material had a propensity to partially disintegrate at high temperatures. In earlier tests, portions of the material had disappeared. The third method tested used a ceramic wool material in the mount. This mount method was similar to the IF&P design with the gasketing material being the primary difference. The ceramic wool is capable of withstanding the high temperature environment and it provided some cushioning or shock-absorption of the candle which extended the candle life. This mount was the favored method.

A 100 hour material test was attempted as HESR-23. Combustor operation was not stable. Large fluctuations were observed in the air assist and primary air pressures, leading to erratic flows and difficulty in controlling test parameters. In checking the system for the source of the air problem, the air assist was lost which led to the subsequent plugging of the injector, only 5 hours into the run. After several unsuccessful attempts to clear the injector, a shutdown procedure was initiated. Post-test inspection of the rig revealed a faulty air assist turbine flowmeter. After several attempts to clean it, no progress was achieved. The flowmeter was sent back to the manufacturer for recalibration. The heaters and material samples were installed for this test. Although sample section inlet temperatures reached only 949°F, with material highs of 675°F, the heaters worked well with no complications encountered.

The test objective of HESR-24 was to expose the materials to the combustion exhaust for 100 hours, however, a number of problems occurred throughout the run resulting in a premature termination. These problems included an air leak out of the material sample section, which resulted directly in the run termination, a heater failure, erratic candle operation, frozen slag accumulations around the impactor, and plugging of the injector.

In the initial stages of the run, the ΔP across the candle gradually increased to a high of 5 psid. Pulse cleaning was effective initially, however, sticky ash was severe enough that pulse cleaning eventually had little effect. It was at this point in the run that the injector plugged, combustor pressure was lowered, and the fuel was switched back to DF#2. Upon resumption of CWM, the candle appeared to be operating normally with a differential pressure ranging between 1 and 2 psid. It was assumed that the relatively rapid changes that occurred when the injector plugged unseated the candle enough to allow a leak of gas and ash. An unseated candle was observed in post-test inspection.

Another problem encountered was with the impactor area. As soon as the rig was changed over to CWM, the impactor temperatures began to fall. After approximately 12.5 hours into the run the temperature at the impactor read 1730°F, much lower than expected at that time. Such temperatures are indicative of frozen slag accumulations.

The heaters/sample section was another problem area. Roughly 12 hours into the run, it appeared that the heaters were not working properly. The materials seemed to reach a steady state temperature. Although the heater setpoint was continually increased, the heaters did not respond accordingly. In the material sample section spool, a sizeable leak was detected in the instrumentation section where the thermocouples are brought

out from the casing. This leak was great enough, along with the impactor and candle difficulties, to abort the run and initiate a normal shutdown procedure.

Post HESR-24 inspection revealed a slagged over impactor, a slagged primary zone, a glass-like material on the candle, and a heater coil failure. Not much ash was observed in the transition zone going to the filter vessel as had been previously seen. The secondary zone also looked much better as there was little accumulation of ash or slag around the air injection ports.

Upon removal from the filter vessel, a glass-like material was observed on the candle. Once the sticky ash cooled, a hard, brittle substance formed, as had been seen in previous tests. This matter was easily removed. Since the candle experienced no physical degradation, it was reused.

A continuity check of the heaters revealed that the aft one was burnt out. The heaters were removed from the spool and a new method of heating the material samples was investigated. Examination of the heater coils did not expose the nature of the failure. The physical appearance of both coils was the same as upon installation, except for a fine layer of particulate observed on the heaters.

To resolve the slagged over impactor problem, a new primary zone, impactor section, and slag pit were designed and recast. The casings remained the same with only the internal refractory shape being redesigned. The primary zone and the impactor section features a continuous conical shape, shown in Figure 11, with the top of the cone remaining at 4 inches and the bottom of the cone opening up to 8 inches at the base of the impactor spool. This new design did not incorporate an impactor nor does it require the slag to flow down into a slag pit as had been previously attempted. The bottom section of the cone, which sits in the impactor spool, was designed as a removable crucible. With this concept, the slag accumulated in the crucible, partially filling the increased volume. Although the residence time shortened over the course of the run due to the accumulation of slag, it would not significantly affect combustor performance because of the increased impactor spool volume and inherently low flow rate. To decrease down-time, the slag filled crucible could be easily removed after a run, and a new one installed.

The slag pit itself was filled with a silica sand and a refractory board was placed in between the slag pit and impactor spools to fill the void when the spools are tightened down. The slag pit was essentially closed off with the crucible in the impactor spool acting as the new pit. In the event that the original pit was required, the sand could be easily removed.

Due to the inexplicable heater failures, a new strategy of supplementing material sample section heat was developed. The new concept employed the use of a natural gas and air mixture which impinge on a baffle upstream of the material samples. This method relied on the internal combustion of the air and natural gas through a modified torch nozzle. The nozzle tip was shielded by another tube to protect the flame from being extinguished by the passing CWM combustion exhaust. The natural gas was leaned out to a point where it was not required during rig heating.

Figure 11 . Conical Primary Zone and Impactor Section

HESR-25 was performed to test the continuous conical primary zone and impactor section. The rig operated very smoothly during the 4 hour check run. No materials were installed for this test. Boroscoping after the run confirmed that the new primary zone and impact section was successful.

Efforts continued to prepare the Hot End Simulation Rig for the initial 100-250 hour run of the 1000 hour test series. Several modifications were incorporated in the system. Acid resistant parts were installed in the system's hot valves. A shield for the candle filter was installed to prevent sticky, ash build-up on the candle element at the entrance to the filter vessel. Several candle mount modifications were tested. The addition of supplemental heat was found necessary prior to the material sample section to effectively bring the materials up to test temperature. In addition, a conical primary zone and impactor section were designed and tested in the rig.

The main objective of the next test series was to evaluate the modification made to the supplemental heating spool prior to the material sample section. This modification consisted of a torch ignitor which supplies air and natural gas to the spool piece just ahead of the materials. HESR-26 demonstrated that the natural gas would not internally combust as expected. HESR-27 addressed this problem. A small diesel supply was added, in conjunction with the natural gas supply, to act as a pilot. The diesel was used to mix with the air and ignite in the hot, coal combustion exhaust. Once the diesel supply was expended, the natural gas was easily ignited in the stable diesel burn. HESR-27 revealed that a larger diesel supply was required for stable combustion. The supply was modified and HESR-28 was performed. In this test it was found that a larger natural gas orifice was required to effectively supply the torch ignitor.

HESR-29 was to be the first extended test of the new slag separator and modified gas orifice. The test was terminated after the top flange of the filter vessel began to leak, approximately 3 hours into the diesel preheat segment of the run. The filter vessel was disassembled in order to correctly fix the problem. The flange gasket had to be replaced.

A retest of HESR-29 was performed to, again, test the modified natural gas orifice in the material sample section torch. The rig ran smoothly throughout the run even though the usual increasing candle ΔP was observed. CWM was burned for 5.30 hours at an average equivalence ratio of 1.20. Upon reaching 700°F in the material sample section, the torch was auto-ignited on DF#2. However, the torch would not remain lit once changed over to natural gas. The reason was unclear for this failure to light. Cooler temperatures at the secondary outlet were also observed during the run. HESR-30 addressed this concern.

Upon teardown, ashing of the candle was observed in addition to ash particulate on the material samples. Part of the blanket material which surrounds the candle plug had apparently fallen off and, therefore, allowed the entrance to the materials to be exposed to the particulate laden exhaust gas. New blanket was installed and tightly secured with nichrome wire. The light dusting of ash was removed from the materials and the rig was reassembled for the next run.

In view of the last run, all major components of the rig had shown some degree of success. The one remaining obstacle was the candle filter. Figure 12. shows the plot of differential pressure across the candle element versus time during HESR-29. The saw-tooth curve, typical of a candle purge, is shown. However, the curve also shows how the ΔP increased over time and that with each pulse, less and less particulate was purged off of the candle. This was mainly due to the sticky nature of the ash which was seen to form a glass-like coating on the candle. The use of sorbent in the rig was investigated. The sorbent would easily adhere to the ash, making it less sticky and easy to purge from the candle.

The objective of HESR-30 was to vary the CWM fuel flow and the flow split, between primary and secondary air, to survey their effect on secondary outlet temperature. The material sample section torch was also tested. The DF#2 supply for the material sample section torch was also modified to come off of the DF#2 pump and run through the

Figure 12. Differential Pressure vs. Time During HESR-29

micromotion. The rig ran without complications burning CWM for 4.3 hours at an average equivalence ratio of 1.19. The data from this test showed that the secondary outlet temperatures did not appear to vary as much as expected. Recognizing the problems encountered with the injection of natural gas in the material sample section torch during previous runs, it was decided to forego the attempt of burning gas and use only DF#2. During this test the torch was operated with a minimum of diesel needed to maintain the flame. Material temperatures stabilized at a high of 1448°F at the end of the run. The fuel flow was varied for the next test. Emissions data were also recorded.

Post-HESR-30 inspection included viewing the primary zone and impactor section with the boroscope. The results were very positive. Much slag had accumulated on the side walls of the impact zone and on the separator itself. Slag was seen to favor one side of the primary zone walls, however, it still appeared to be flowing down into the impactor section. The reason that the slag was not uniformly distributed along the perimeter of the primary zone was most likely due to the injector not being perfectly centered in the rig. Although the jet may have been off to one side, it was still impacting on the slag separator. No slag was observed in the banana ports leading into the secondary zone nor on the injector tip. The new impactor operated as planned.

A Fibrosic candle was installed in the filter vessel for HESR-31, which was to be a 100 hour extended run; the first in the 1000 hour test series. The rig performed exceptionally well at an average equivalence ratio of 1.20. The candle ΔP did not increase nearly as rapidly as in previous runs and purging had significant, long-term effect on the candle with a very low (0.7 psid, typ) differential pressure observed after purging. Secondary outlet temperatures were observed to be higher than normal reaching beyond the desired 1800°F. At 7.3 hours into the CWM run, a large leak developed in the material sample

section where the material thermocouples are brought out of the rig. The leak was significant enough to terminate the run with an emergency shutdown.

This leak occurred in an area where 14 material thermocouples are brought out through a 1/4 inch opening. Two such openings existed in the material sample section refractory plug. In past runs these openings had been sealed with a high temperature, ceramic adhesive. Apparently the adhesive did not create a proper seal for the thermocouple leads. Therefore, the plug was modified by making the two 1/4 inch openings into one 1 inch hole through the refractory. A salt-shaker style cap was welded to the outside wall of the plug such that all the thermocouple leads were brought out through the holes in the cap and silver-soldered into position creating the seal.

Before the end of the run, material temperature readouts were indicating that the thermocouples may be burning out. Upon removal from the system, it was discovered that many of the thermocouple leads had been corroded causing the erroneous readings. An indepth material evaluation revealed that sulfur in the gas stream had attacked the Inconel sheathed leads. New Hastelloy-X sheathed thermocouples were procured since Inconel does not survive in environments containing any sulfur. In addition to the Hast-X thermocouples upgrade, all hot ball valves, including the backpressure valve, received new seals.

After the material specimens were removed from the rig, the rest of the system was inspected. The combustor was in excellent condition with no slag observed on the injector or in the transition zone into the secondary combustor. Slag was flowing down into the impactor section. The secondary zone was also clean. No slag or ash was observed there as had been seen in previous runs. The new slag separator performed well. The candle was also removed from the filter vessel and cleaned. The same glass-like ash was adhered to the candle as has been seen after previous tests. During cleaning, as some of the ash was imbedded so deeply into the filter element, some of the filter material was also removed leaving pitted areas on the candle. The majority of the ash was easily removed and the candle reinstalled in the vessel. An ash sample was collected with the results of the analysis shown in Table 7.

HESR-32 was performed to expose the material specimens to exhaust at design conditions. The rig ran quite smoothly with increased material temperatures as expected. Using a low ash coal appeared to diminish the ashing of the candle. The fuel properties of this low ash coal are shown in Table 8. Typical differential pressures across the candle were on the order of 0.5-1 psid after 3 hours on coal. In previous runs these numbers were on the order of 1.5-3 psid after the same amount of run time.

Once the material sample section reached 700°F, the diesel line was opened and the torch auto-ignited. As temperatures rose, the material temperature controllers began indicating much higher readings than the other material temperatures shown on other data acquisition equipment. It was at this point that the controllers started giving error readings indicating open thermocouples. However, a instrument check of several of the material thermocouples revealed that none were open. Without the controllers metering in the cooling air to the materials, there was no point in continuing the test, so a shutdown was initiated.

Table 7. Chemical Analysis of Ash From HESR-31

Compound	Wt (%)
Fe ₂ O ₃	24.37
SiO ₂	38.78
Al ₂ O ₃	29.13
K ₂ O	2.43
Na ₂ O	1.60
CaO	0.41
NgO	0.55
NiO	0.13
Cr ₂ O ₃	0.65
ZnO	0.05
TiO ₂	1.38
MnO ₂	0.14
CuO	0.17
PbO	0.04
CoO	0.04

Further investigation revealed that the controllers were not properly calibrated and that the thermocouples themselves were grounded, contributing to the erroneous readings. The grounded thermocouples were sent back to the manufacturer for modifications and the temperature controllers recalibrated correctly and tested.

Ungrounded thermocouples were attached to the materials in the sample section to resolve the difficulties experienced with the material temperature controllers. Testing resumed with HESR-33 being performed to expose the Fibrosic candle filter and the material samples to the low ash CWM exhaust for an extended period of time.

The rig ran uninterrupted for 14 hours on coal slurry fuel. The low ash coal did not plug the candle as quickly as the other coals used. After 14 hours, hot spots were observed at several places on the stainless exhaust piping. Attempts were made to increase cooling to this area, but to no avail, and a shutdown procedure was initiated.

Table 8. Fuel Properties of Low Ash CWM Used in HESR-32

CWM		R-8
Coal Source		Elkhorn #3
Slurry Composition		
Moisture Content (wt%)		45.77
Coal Content (wt%)		54.05
Ash Content (wt%)		0.25
A-23 (wt% of coal)		0.32
Flocc (wt% of coal)		None
Particle Size		
% Passing	100 micron	99.93
% Passing	75 micron	99.89
% Passing	53 micron	99.70
% Passing	45 micron	98.98
% Passing	37 micron	98.78
% Passing	30 micron	94.28
% Passing	20 micron	84.70
% Passing	15 micron	72.68
% Passing	10 micron	58.67
% Passing	8 micron	48.08
% Passing	6 micron	37.00
% Passing	4 micron	27.80
% Passing	3 micron	21.38
% Passing	2 micron	17.59
% Passing	1 micron	6.27
Mean Size (micron)		11.3
Slurry Viscosity (cp)		
@ 100/sec		310
@ 1000/sec		480
Slurry LHV (Btu/lb)		7539
Coal Characteristics		
Proximate Analysis (wt%)		
Ash		0.46
Volatiles		36.68
Fixed Carbon		62.86
Ultimate Analysis (wt%)		
Carbon		85.67
Oxygen		6.64
Hydrogen		5.47
Nitrogen		1.47
Sulfur		0.75
Ash Composition (wt%)		
SiO ₂		23.47
Al ₂ O ₃		20.16
Fe ₂ O ₃		22.01
CaO		7.72
MgO		1.10
Na ₂ O		5.62
K ₂ O		0.71
TiO ₂		4.97
MnO ₂		0.09
P ₂ O ₅		0.21
V ₂ O ₅		0.22
PbO		<0.01
SO ₃		7.53
Ash Fusion Temperature (°F) Oxidizing/Reducing		
Initial Deformation		2382/2085
Softening		2432/2099
Hemispherical		2476/2105
Fluid		2534/2330

The combustor ran very smoothly on coal slurry fuel. The primary and secondary combustion zones reached design temperatures, with the secondary outlet temperature attaining 1950°F. No injector difficulties were encountered during the coal run. Although during shutdown the injector did plug due to inadequate pump pressure on the diesel side. The injector was unable to be cleared, therefore the normal diesel shutdown was not followed.

The candle responded to the low ash coal as expected. Differential pressure across the candle was slow to increase. Towards the end of the run, the ΔP was observed to increase 1 psi per 2 hours. Prior to shutdown, the ΔP across the candle registered at 4.1 psid. If the premature shutdown was not initiated, the rig would have only been operated for several more hours due to the plugging of the candle.

The Fibrosics candle had seen several hours of CWM and diesel operation in the Hot End Rig. The data shown is from HESR-33. In Figures 13 and 14, it is apparent that the candle was operating as expected in the beginning of the run, but manifested the usual plugging attendant with the sticky ash generated with this system. It is noteworthy that the candle performed in a somewhat textbook manner in the beginning of the run. Several sawtoothed cycles are apparent as the differential pressure across the candle would increase to the level of 2-3 psid at which point a purge cycle would occur. The differential pressure would drop significantly and a new filtering cycle would take place. This pattern continued for several hours. There were occasions when combustor pressure had dropped or increased above its setpoint necessitating adjustment of the backpressure valve. This type of adjustment affected the differential pressure across the candle as the system responded. For instance, a lowering of the combustor pressure resulted in the higher velocity of gas passing through the candle for a short period of time. During this brief period, the differential pressure across the candle was expected to increase.

Unfortunately, a faulty pressure transducer line wire prevented any differential pressure data from being acquired for the first 6 hours of the run. A redundant pressure gauge was used by the operators to monitor candle performance. During this period, candle performance is best described as "normal" based on log entries.

The diesel torch was easily ignited in the material sample section. Material temperatures continued to increase prior to shutdown. The samples reached a high of 1753°F, on the high temperature materials. Two temperature controllers, which meter the cooling air to the samples, began to give false signals indicating there was a problem. These controllers are for the two lowest temperature material pairs. Subsequently, cooling air was not being properly metered allowing the samples to reach temperatures beyond their setpoint.

Post-HESR-33 inspection of the rig was very encouraging. The primary zone combustor had to be disassembled in order to clear the fuel injector, which was easily accomplished. Examining the impactor section/slag pit, slag was forming and dripping into the pit area as designed and is shown in Figure 15. Slag flow was also very encouraging, with a uniform coating of the primary zone walls, and no slag around the injector.

Figure 13. Fibrosics Candle Performance Data for 6-10 Hour Period

The candle filter had an unusual color gradient as seen in Figure 16. The cause of this is unknown. It is presumed that the candle experienced various surface temperatures at different locations on the candle, leading to the varied discoloration.

Results of HESR-33 indicate that with the existing system, runs would not exceed more than 16 hours in duration, due to candle plugging. It is believed that sorbent injection would have alleviated this problem. Sorbent feeders were investigated. No further testing was to take place until a viable sorbent injection system would be verified. Also during this downtime, a water spray assembly was fabricated and installed downstream of the material sample section to quench the exhaust prior to entering the stainless exhaust piping. Hot spots in this area were detected during HESR-33 causing the premature shutdown.

An analytical study was performed on a sample of the glass-like ash that adheres to the candle and prevents purging of the filter. X-ray diffraction as well as X-ray emission, using electron beam microprobe methods, were done in order to characterize the material. The results of this study indicated that the major phase of the ash sample is

Figure 14. Fibrosics Candle Performance Data for 10-14 Hour Period

an iron oxide spinel; a solid solution compound based on Fe_3O_4 . A lesser amount of hematite (Fe_2O_3) was also present along with alpha-quartz. A minor amount of small gamma-aluminum oxide (Al_2O_3) also exists. These were the only crystalline phases of the sample material. No other crystalline forms were present. The spectrochemical data is shown in Table 9.

Two sorbent injection suppliers were identified for the feed system prior to the filter vessel. Both designs feature an enclosed, pressurized screw feeder system guaranteeing flow rates as low as 1 pph.

SUMMARY

Long-term rig reliability has been improved. A conical primary zone and impactor section was developed and tested to allow for slag accumulation during 250 hour tests. A candle filter shroud protected the element from direct impingement of particulate, which previously led to blinding of the candle. A flexible candle mount system had been

Figure 15. Impactor/Slag Pit Area Post-HESR-33

Figure 16. Fibrous Candle Filter Post-HESR-33

Table 9. Spectrochemical Data From Analysis of HESR Candle Ash

Element	Area 1	Area 2
Aluminum	15.5	19.6
Iron	48	46
Sodium	0.47	0.72
Silicon	20.7	27.7
Potassium	1.25	1.38
Calcium	2.6	2.85
Titanium	1.72	1.63
Manganese	0.50	0

established and was proven successful during extended testing. Supplemental heating of the material sample section was modified and demonstrated effectively. Still recommendations were needed to ensure rig longevity.

The injection of sorbent into the system would have greatly influenced rig life. This would have reduced the stickiness of the ash and the formation of glass-like material enabling the candle to be purged more completely resulting in longer test durations. A mini Particle Rejection Impact Separator (PRIS) incorporated into the system would also have been beneficent in, again, providing a more workable ash. However, no further HESR work was done due to the restructuring of the program.

**DATE
FILMED**

6 / 22 / 94

END