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**ADVANCED COAL-FUELED INDUSTRIAL COGENERATION GAS TURBINE
SYSTEM**

Annual Report for the Period June 1990-June 1991

**By
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C. S. Wen**

July 1991

Work Performed Under Contract No. AC22-86MC23166

**For
U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
Solar Turbines, Inc.
San Diego, California**

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ABBREVIATIONS AND SYMBOLS

AMAX	Amax Research & Development Center
APCD	Air Pollution Control District (San Diego County)
B&W	Babcock & Wilcox
CWt 1	Coal-Water Mixture
DCF 1	Direct Coal Fired Turbine
EDX	Energy Dispersive X-Ray
EU	Engineering Units
HESR	Hot End Simulation Rig
HWD CSF	Hot Water Dried Coal Slurry Fuel
IBSTF	Integrated Bench Scale Test Facility
MAF	Moisture and Ash Free
PHDL	Pressurized Hydrated Dolomitic Lime
PRIS	Particulate Removal Impact Separator
SEM	Scanning Electron Microscopy
SMD	Sauter Mean Diameter
TSSC	Two Stage Slagging Combustor
UNDEERC	University of N. Dakota Energy & Environmental Research Center
XRD	X-Ray Diffraction
cp	centipoise
fpm	feet per minute (face velocity - cubic feet gas per minute/square feet filter area)
gal/hr	gallons per hour
MMBtu	million British Thermal Units (based on Lower Heating Value)
MMBtu/hr	million British Thermal Units per hour (based on Lower Heating Value)
msec	millisecond
P_{in}	inlet air pressure
ppb	parts per billion
ppbw	parts per billion by weight
pph	pounds per hour
ppm	parts per million
ppmm	parts per million by mass
ppmv	parts per million by volume
ppmw	parts per million by weight
psi	pounds per square inch
psid	pounds per square inch differential
psig	pounds per square inch gauge
T_{in}	inlet air temperature
T_m	melting point, absolute temperature
T_{outlet}	secondary combustor outlet temperature
μm	micron

Note: Gaseous emissions (NO_x , CO, UHC, & SO_2) are quoted in parts per million by volume corrected to 15% oxygen in the exhaust on a dry basis unless otherwise specified.

1. INTRODUCTION

Advances in coal-fueled gas turbine technology over the past few years, together with recent DOE-METC sponsored studies, have served to provide new optimism that the problems demonstrated in the past can be economically resolved and that the coal-fueled gas turbine can ultimately be the preferred system in appropriate market application sectors.

The objective of the Solar/METC program is to prove the technical, economic, and environmental feasibility of a coal-fired gas turbine for cogeneration applications through tests of a Centaur Type H engine system operated on coal fuel throughout the engine design operating range.

The five-year program consists of three phases, namely:

- Phase I - System Description
- Phase II - Component Development
- Phase III - Prototype System Verification

A successful conclusion to the program will initiate a continuation of the commercialization plan through extended field demonstration runs.

2. SUMMARY

This report covers the activity during the period from 2 June 1990 to 1 June 1991. The major areas of work include: the combustor (sub-scale testing and full size design and fabrication), cleanup, coal fuel specification and processing, and the Hot End Simulation rig.

To date Solar has demonstrated:

- Stable and efficient combustion burning coal-water mixtures using the Two Stage Slagging Combustor.
- Molten slag removal of over 97% using the slagging primary and the particulate removal impact separator

During the past year the following tasks were completed:

- A continuous slag removal system was tested on the scale combustor providing design information for the full size configuration
- Completed an evaluation on coal-water mixture properties on combustor performance
- Procured new stronger candle filters for evaluation in the Integrated Bench Scale Test Facility

During the past year the following tasks were started:

- Testing of the full size combustor at the Caterpillar Tech Center in Peoria, Illinois
- Development of a Lean Particulate Removal Impact Separator as an alternative to the ceramic barrier secondary filter
- Work at Purdue University on an alternate fuel injector design which will significantly reduce the amount of air assist required
- Design of the turbine modifications required to integrate the combustor island with the engine

Combustor testing during the past year has included work on the two subscale combustors (the TSSC and the IBSTF) and the full size combustor. Some of the testing was devoted to developing a continuous slag removal system. A system which featured a water bath into which the molten slag drops was tested on the TSSC rig. The quenched slag is removed through a lock hopper arrangement. Results were promising and provided adequate data and information for the design of the full size system which will be required for the proof-of-concept engine test in Phase III.

A series of tests, 10 in all, were run on the TSSC rig to evaluate the effects of CWM properties on combustion performance. The CWM properties which were varied included: loading, top size,

ash concentration, additives and source seams. Loading was varied from 50% to 58.2% with little effect on performance (NO_x , slag capture, carbon conversion and outlet temperature). Increasing the loading results in increased pumping and handling problems. The ash concentration ranged from 3.7% to 12.8%. Carbon conversion and slag capture appeared to increase with increasing ash content. Other parameters were not effected. Higher coal ash did result in faster refractory degradation. CWM's with particle top sizes of 25, 45 and 75 μm were tested with little noticeable effect on combustor performance. The slag capture appeared to be the highest with 45 μm top size. CWM's from four different coal seams were evaluated. There was no significant difference in combustor performance. The highest carbon conversion was obtained with a coal with the lowest volatile content and the highest slag capture occurred with a coal with high iron content in the ash.

The full size combustor was designed, fabricated and installed at the Caterpillar Tech Center in Peoria, Illinois. Following a series of checkout tests using diesel fuel the first coal burning test occurred on May 23, 1991. Test duration on coal was 2.5 hours, operation was stable and initial performance data were as expected. However the primary to secondary zone flow split was not optimum and the exhaust system (back pressure valve) is undersized so that desired operating conditions could not be maintained throughout the test. Post test inspection revealed that the impactor had failed possibly due to incomplete curing of the refractory. Corrections to these problems are in process.

The failed silicon carbide rods in the subscale Particulate Removal Impact Separator (PRIS) were analyzed. The failures experienced were due to degradation by reactions of iron from the coal ash with silica from the rods which forms an iron silicate which is easily eroded. The subscale PRIS has been rebuilt with alumina rods and has accumulated a minimal amount of time on coal, however a 50 hour test of the rig is scheduled shortly. The full size PRIS was designed based on experience gained from the subscale unit and on results from a full-size flow model. Fabrication of the full-size PRIS is complete except for the spool section with the rods. Rod material selection is deferred until the end of the 50 hour test mentioned above. The full-size PRIS will be integrated into the rig as soon as it is available.

A second set of ceramic candles was procured. These candles, from a different vendor, are stronger and do not have the transition zone from dense to filtering in the area where failures have occurred. After review of the candle failures reported in the last annual report a program was established which included testing the second set of candles, conducting flow tests of the vessel, and retaining a consultant. The test program has been hampered by the necessity to install a venturi scrubber to meet local APCD particulate limits so that a permit to operate can be issued.

As an added task in the revised program work was started on a lean PRIS to replace the ceramic barrier filter. This device would be based on the rich zone PRIS already tested but would vary in that it operate in a lean zone at temperatures below the slagging temperature of the coal ash. A number of approaches being considered including the addition of materials to make the mineral matter fluid.

In the area of coal fuel specification development a number of significant activities took place. A large lot of CWM (~4500 gallons) for the full-size testing was prepared by AMAX and delivered to the Caterpillar Tech Center in Peoria. The storage tank and associated pumps, heaters and

stirring equipment were installed and checked out. So far no major problems have occurred, but it is obvious that the logistics of supplying CWM for the engine test in Phase III indicate that on-site slurry preparation had to be considered. To investigate that scenario a Drais Mill system with capacity to support the subscale rigs was leased. It has been setup and is ready to start preparing slurry on-site to be burned in the TSSC. The fuel cost spreadsheet has been updated to project Centaur Type H fuel costs for various scenarios.

A number of test runs and modifications have been made in the Hot End Simulation Rig (HESR) in an effort to be able to run long duration tests. Because of the low fuel firing rate selected to minimize fuel costs heat loss is a serious problem. In order to maintain the gas temperature at the sample section electric heaters were installed immediately upstream of the sample section. Installation problems have occurred and are being addressed along with a review of other heating schemes. Some work was accomplished with the candle installation and mounting. This included evaluation of gasket materials to provide a gas tight seal and the installation of a shroud to prevent direct impingement of the gas on the candle. One of the new stronger candles obtained for the next run in the IBSTF has been tested in the HESR with very encouraging results.

Phase III activities were started in March 1991. The initial activity is the design and procurement of the hardware to convert a standard Centaur Type H so that the coal-fueled combustor island can be integrated. The turbine inlet scroll will be steam cooled in order to accommodate the required turbine inlet temperature of approximately 1920°F and to trim the radial inlet temperature profile. Planning and selection of equipment for the engine test site is also in progress.

3. PHASE II - TASK 1 - COMBUSTOR DEVELOPMENT

3.1 SPECIFIC ITEMS OF PROGRESS

3.1.1 Subscale Combustor Testing

- Development of a subscale continuous slag removal device has continued. An increase in distance between the slag tap and water bath has proven to be effective in getting all the slag to flow through the impactor. Bridging of slag below the slag tap has been observed.
- A series of CWMs possessing different properties have been formulated and evaluated in ten combustion tests. The properties that have been studied include coal loading, ash concentration, particle size, CWM additives, and several coal seams.

3.1.2 Full-Scale Combustor Development

- The full size primary and secondary combustors without the PRIS have been installed for testing at the Caterpillar Technical Center in Peoria, Illinois. A shake-down and calibration procedure has been completed.
- Two tests have been completed to cure the refractory and demonstrate the combustor operation on DF #2. Refractory curing was completed by ramping up the air temperature over an approximate nine hour period and then starting diesel combustion. In the first test diesel combustion was maintained for only 10 minutes due to facility problems. The second test was run to complete the refractory curing process by burning diesel fuel for three hours.
- CWM combustion was completed the first time in Test No. 4 following a failed attempt in Test No. 3. The combustor operated stably on CWM reaching anticipated outlet temperatures. The back pressure valve was undersized resulting in a lowering $\Delta P/P$ as the test proceeded. The flow split was below design at 2.3.

3.2 DISCUSSION

Combustion testing has been completed on the subscale Two-Stage Slagging Combustor (TSSC) and the Full Size Combustor. In addition, scaled combustion tests to evaluate the clean-up devices have been completed in the Integrated Bench Scale Test Facility (IBSTF). This facility is detailed in Section 4.0. The TSSC and the Full Size Combustor hardware have been configured for testing described in this report with only primary and secondary combustors. The TSSC has been used to complete development of a continuous slag removal device and to evaluate a series of fuels with different properties. The tests completed in the TSSC in this reporting period are summarized in Table 1. The tests completed in the Full Size Combustor are summarized in Table 4.

3.2.1 Subscale Combustor Testing

Continuous Slag Removal

The continuous slag removal device development has continued in this reporting period. Preliminary work has been completed using a batch water bath and a water bath and lock hopper arrangement. The slag pit geometries tested are included pictorially in Figure 1.

The water flush slag pit has been modified to enhance the heating capacity of the slag tap hole. An illustration of the slag tap and water bath designated as Design #4 is shown in Figure 1(D) with other slag tap geometries tested. The design has been modified by increasing the distance from the slag tap to the water line, by inserting radiant heat shields directly below the slag tap, and by modifying the slag tap torches to allow continuous operation. This slag tap configuration has been tested in TSSC No. 47. Operating conditions and test results are summarized in Tables 1 and 2. Table 2 also includes data taken in TSSC Tests Nos. 45 and 46 for comparison.

Testing has been completed in the TSSC configured as illustrated in Figure 2. This configuration has required that the height of the primary zone be decreased from 24 inches to 16 inches. The height has been decreased because of limitations of the test facility. A decrease in primary zone height results in less available combustion residence time. In past tests slag capture has been influenced the greatest by decreased primary zone height.

Test No. 47 lasted for two hours on CWM. The slag tap torches were operated throughout the test while burning DF#2 and CWM using a natural gas input pressure drop of 57 psid. The torches used primary air at 620°F and 4% pressure drop. A thermocouple measuring slag tap gas temperature reached a maximum of 2600°F before switching to CWM. Refractory wall temperatures measured at the impactor and below the slag tap reached maximums of 2483°F and 2049°F, respectively. The water flush system was operated six times yielding 3 to 5 lbs of slag. The slag collected in the lock hopper was largely in the form of pellets.

In post test inspection the primary zone and injectors were in good shape, but the impactor showed some erosion. The area below and around the impactor was coated with slag but was free of any accumulations indicating that adequate temperatures in the region above the slag tap were achieved to insure slag flow. A total of 5.8 lbs of slag was collected in the lock hopper and water bath. A 2.25 lb piece of slag was bridged across the radiant heat shields below the slag tap. Apart from this slag bridge the remainder of the insulation comprising the radiant heat shields was free from slag. The slag bridge may be a result of the torch gas flow but this is unknown. This problem can be averted in the full scale design by slightly increasing the insulating inside diameters below the slag tap. The total slag capture has dropped to 45% with this TSSC configuration. The drop in slag capture is attributed to the decrease in primary zone height as described earlier.

This test concludes the design investigations of the continuous slag removal system. In this test successful slag tap heating was achieved through the use of slag tap torches. Nearly all the slag separated in the primary zone flowed through the slag tap. The slag collected in the water was

Figure 1. Slag Removal System

small enough to be handled by a moderately sized purge valve and lock hopper. The system used in this test demonstrated removal of 50 to 75% of the slag collected by the impactor into a lock hopper from the primary zone. This was accomplished despite the design limitations which had the slag collect in a pipe with a large dead space unaffected by purging.

As a summary the following are important observations and design criteria that will be useful in full scale slag removal system design:

- 1) The presence of a water bath below the primary zone has no detectable impact on the operation of the combustor.
- 2) Slag that is quenched in a water bath after dripping through a slag tap is largely in the form of slag pellets of 0.25 to 0.325 inch diameter. The slag is very brittle and easily crushed by hand. This information indicates that an auger/crusher is not necessary.

Table 1. Summary of CWM Testing of Fuels of Varying Properties

Test No.	48	49	50	51	52
CWM (critical property)	"S1"	"S3" (High Coal Load)	"S4" (Low Coal Load)	"S6" (med. ash)	"S7" (high ash)
T _{in} (°F)	653	652	625	626	639
P _{in} (psig)	79.5	78.4	75.7	76.7	76.0
φ _{primary}	1.42	1.43	1.55	1.47	1.38
ΔP/P (%)	3.9	3.9	4.1	4.0	4.1
Heat Input (MMBtu/hr)	4.66	4.71	4.67	4.36	4.20
T _{outlet} (°F)	1962	2107	2107	1997	1968
RESULTS					
Emissions @ 15% O₂					
NO _x (ppmv) (lbm/MMBtu)	53.3 (0.2225)	68.1 (0.3040)	86.3 (0.3885)	71.70 (0.3050)	67.23 (0.2880)
CO (ppmv) (lbm/MMBtu)	6.1 (0.0155)	3.2 (0.0083)	7.6 (0.0204)	12.9 (0.0344)	11.8 (0.0304)
SO ₂ (ppmv) (lbm/MMBtu)	N/A	178 (1.064)	107 (0.6664)	N/A	257 (1.5323)
Particulate (ppmm)	2034.1	455.2	1584.9	1167.2	750.2
Carbon Conversion (%)	97.2	99.7	97.2	99.0	99.8
Ash Balance					
Primary Zone Slag Capture (%)	37.2	23.9	28.9	26.0	46.0
Ash Emitted (%)	92.9	26.7	53.6	24.2	14.8
Imbalance (%)	-30.1	49.3	17.4	49.3	39.1
(lbs)	-5.8	10.0	4.63	24.2	39.4

Table 1. Summary of CWM Testing of Fuels of Varying Properties (Continued)

Test No.	53	54	55	56	57	58
CWM (critical property)	"S5" (no additives)	"S6" (fine grind)	"S9" (coarse grind)	"S10" (Upper Freeport)	"S11" (Soldier Creek)	"S12" (Illinois No. 6)
T _{in} (°F)	624	624	628	654	627	618
P _{in} (psig)	79.9	76.1	79.7	76.0	77.0	76.0
φ _{primary}	1.297	1.49	1.50	1.44	1.42	1.36
ΔP/P (%)	3.90	4.0	4.0	3.9	4.0	4.10
Heat Input (MMBtu/hr)	4.46	5.66	4.95	4.11	4.52	4.48
T _{outlet} (°F)	1794	2001	2038	1971	2011	1970
<u>RESULTS</u>						
Emissions @ 15% O₂						
NO _x (ppmv) (lbm/MMBtu)	81.90 (0.3833)	70.15 (0.3100)	65.20 (0.2850)	55.40 (0.2783)	52.00 (0.2350)	43.80 (0.2100)
CO (ppmv) (lbm/MMBtu)	109.7 (0.3127)	19.8 (0.0540)	11.7 (0.0310)	20.9 (0.0637)	15.9 (0.0450)	23.5 (0.2110)
SO ₂ (ppmv) (lbm/MMBtu)	156 (1.0081)	156.1 (0.9461)	84.7 (0.5250)	129.0 (0.9095)	N/A	40.7 (0.2730)
Particulate (ppmm)	747.0	1038.7	872.0	169.6	235.5	1076.1
Carbon Conversion (%)	98.4	97.9	98.5	99.8	99.6	98.1
Ash Balance						
Primary Zone Slag Capture (%)	22.0	21.0	18.0	31.0	23.0	54.0
Ash Emitted (%)	25.8	28.4	25.1	3.2	7.4	20.8
Imbalance (%)	9.5	51.0	57.4	65.9	69.2	19.6
(lbs)	52.2	(15.1)	(16.9)	42.8	24.8	9.4

Table 2. Summary of TSSC Combustor Testing of Slag Removal System

Test No.	45	46	47
Slag Design	1	2	4
CWM	T	T	T
T _{in} (°F)	638	636	644
P _{in} (psig)	76	75	61
T _{outlet} (°F)	1933	1960	1798
Φ _{primary}	1.39	1.37	1.38
NO _x (ppm)	49.0	48.8	44.3
(lbm/MMBtu)	(0.1976)	(0.1950)	(0.1781)
CO (ppm)	2.6	2.2	4.3
(lbm/MMBtu)	(0.0068)	(0.0050)	(0.0103)
ΔP/P Primary (%)	4.1	4.0	4.0
Slag Capture (wt%)	70	--	45
Heat Input (MMBtu/hr)	4.70	5.08	4.03

- 3) In subscale testing slag tap heating is required for the slag to flow through the slag tap. In the full scale this may not be true because of the decreased surface area to volume ratio and the increased slag flow rate. The design of the slag tap heating arrangement is a critical part of the system.
- 4) An isolation valve can be used to purge most of the slag from the water bath into a lock hopper with no noticeable impact on the system.
- 5) Design of the passage from the slag tap to the water bath must be sufficiently large to prevent slag bridging while minimizing heat loss.

Fuel Property Specification Testing

As a means of assessing the flexibility of the TSSC design on using a wide range of CWM fuels a series of tests have been completed with fuels formulated with a range of properties. The testing is to determine if any fuel specifications need to be set for the Coal-Fueled Centaur. The fuel properties that were varied include the coal loading, the ash concentration, the particle size, fuel additives, and bituminous coals from several regional seams. The fuel tests have been completed in the TSSC configuration with the water quench slag removal system as illustrated in Figure 2. As indicated above this configuration has a decreased primary zone height of 16 inches to accommodate the slag removal design.

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Figure 2. TSSC Test Configuration for Evaluation of Fuels of Varying Properties

A listing of all the fuels used and their properties are included in Table 16. The tests completed with these fuels and the important results are summarized in Table 1.

Analyses of particulate samples have been completed to provide the carbon conversion and particulate emissions data included in Table 1. This data were taken with the isokinetic sampling probe. The sample is drawn for a four minute period. The sample is quenched with deionized water and separated from the gas stream in a condensation bath with two gas cyclones and filters. The analyses of the samples for the ten tests are included in Table 3.

Coal Loading

The influence of CWM coal loading has been investigated burning CWM's of loadings of 54.0, 58.2, and 50.0% in TSSC Test Nos. 48, 49, and 50, respectively. A summary of the CWM properties of these fuels is included in Table 16. The table illustrates that while slight variations

**Table 3. Particulate Sample Analyses From Test Completed In TSSC
With CWMs of Varying Fuel Properties**

Test No.	48	49	50	51	52	53	54
CWM	"S1"	"S3"	"S4"	"S6"	"S7"	"S5"	"S8"
Solids (g)	19.28	4.82	15.87	11.35	7.38	8.51	58.6
Carbon (%)	40.5	16.1	51.4	11.35	7.38	8.51	58.6
Ash (%)	59.5	83.9	48.6	25.4	6.8	58.3	41.4
Water	11.8	16.0	11.9	10.7	13.6	13.4	8.1
pH	2.0	2.5	2.5	2.0	2.3	2.5	2.5
Ash Analysis (%)							
Al ₂ O ₃	12.63	11.75	26.63	27.86	24.12	22.47	28.08
Fe ₂ O ₃	84.40	68.31	24.48	26.64	17.23	32.40	22.90
SiO ₂	15.19	12.04	34.43	35.58	47.75	36.11	38.75
CaO	0.13	2.48	5.78	0.15	3.73	3.33	0.15
K ₂ O	3.58	1.37	2.95	1.85	1.57	1.15	1.90
Na ₂ O	1.58	1.08	1.35	1.42	2.34	1.75	2.16
TiO ₂	0.73	0.77	1.80	1.94	0.97	0.62	2.11
MnO ₂	0.45	0.47	0.16	0.09	0.08	0.20	0.11
Cr ₂ O ₃	0.52	0.45	0.34	0.34	0.28	0.58	0.58
NiO	0.18	0.42	0.28	0.15	0.15	0.17	0.16
CuO	0.14	0.35	0.21	0.07	0.08	0.12	0.08
MgO	0.29	0.27	0.55	1.27	1.02	0.43	0.82
SO ₃	--	0.25	0.04	0.28	0.04	0.17	0.41
PbO	0.10	0.10	0.89	0.08	0.08	0.06	0.07
ZnO	0.09	0.10	0.02	2.01	0.09	0.11	0.34
Water Analysis (ppmm)							
SO ₄	437.5	228.0	620.0	350.0	320.0	240.0	304.0
Cu	99.43	7.37	110.5	4.84	27.30	19.90	35.3
Fe	30.80	10.70	36.8	40.00	16.90	17.70	30.20
Al	9.79	2.54	13.24	5.40	3.68	7.36	15.80
Si	5.29	2.27	8.64	3.60	1.67	3.33	7.05
Na	18.89	1.31	3.10	1.75	0.81	1.82	8.70
Mn	2.29	1.22	1.14	0.01	0.68	0.87	1.43
Cr	1.58	0.83	2.96	7.60	0.91	1.14	1.64
Ca	2.98	0.68	1.56	1.07	0.64	1.14	2.01
Mg	3.08	0.65	1.19	0.78	0.34	0.34	3.87
K	2.81	0.57	1.85	1.45	0.62	0.60	1.45
Ni	1.27	0.35	1.68	5.90	0.99	1.25	1.07
Zn	0.47	0.37	0.30	0.27	0.11	0.11	0.19
Li	0.02	0.01	0.03	0.10	0.10	0.01	0.01

**Table 3. Particulate Sample Analyses From Test Completed In TSSC
With CWMs of Varying Fuel Properties (Continued)**

Test No.	55	56	57	58
CWM	"S9"	"S10"	"S11"	"S12"
Solids (g)	8.32	1.58	2.39	10.97
Carbon (%)	56.2	30.4	47.1	54.6
Ash (%)	43.8	69.6	52.9	45.4
Water	10.8	12.1	9.10	3.5
pH	2.0	2.0	2.5	4.0
<u>Ash Analysis (%)</u>				
Al ₂ O ₃	30.80	28.06	20.5	23.5
Fe ₂ O ₃	18.21	16.74	17.1	28.2
SiO ₂	37.46	45.1	52.2	36.0
CaO	3.98	1.68	1.61	0.56
K ₂ O	2.42	2.61	2.55	3.16
Na ₂ O	2.02	1.26	1.75	3.29
TiO ₂	1.98	1.60	1.54	1.49
MnO ₂	0.13	0.08	0.10	0.35
Cr ₂ O ₃	0.61	1.05	0.51	0.75
NiO	0.36	0.30	0.41	0.27
CuO	0.16	0.09	0.09	0.07
MgO	0.68	0.91	1.14	1.13
SO ₃	0.59	0.23	0.20	0.18
PbO	0.08	0.09	0.09	0.05
ZnO	1.02	0.14	0.05	0.15
<u>Water Analysis (ppmm)</u>				
SO ₄	0.59	275.	250.0	180.0
Cu	75.20	26.1	30.5	2.38
Fe	29.0	10.63	7.81	31.3
Al	17.50	34.2	6.32	7.59
Si	8.08	1.77	4.12	8.33
Na	9.18	4.20	3.50	16.0
Mn	1.03	0.49	0.33	3.14
Cr	1.53	0.79	0.33	1.25
Ca	2.07	2.29	3.04	15.2
Mg	1.18	1.12	1.28	0.05
K	3.20	2.61	0.96	3.33
Ni	0.80	0.63	0.23	15.9
Zn	0.37	0.15	0.08	0.44
Li	0.02	0.01	0.02	0.02

in fuel property exist the largest variation of the CWM's is in coal loading. Coal loading influences several of the parameters listed in Table 16 in particular; slurry viscosity, slurry LHV, and to a lesser degree CWM ash content. Efforts were made to control viscosity through the addition of stabilizer and dispersant, but for a non-newtonian fluid the viscosity will vary independently of shear rate. The CWM's listed in Table 16 have the same viscosity of 300 cp at 100 sec^{-1} , but at 1000 sec^{-1} vary from 185 to 500 cp.

The fuel handling properties varied substantially between the CWMs of three different loadings. CWMs "S1" and "S4" were readily pumped through the system and into the combustor. "S3" of higher loading was more difficult to pump resulting in higher pump pressures and larger variations in fuel flow rate. The difficulty in pumping each fuel appears to be proportional to the viscosity at 1000 sec^{-1} . While fuels of loadings in excess of 58% could be efficiently utilized in the combustor a refinement to the pumping system would be required.

The combustor exhibited good operation with all three fuels. The combustion tests were operated at nearly identical conditions as listed in Table 1. The largest variation in test conditions was in primary zone equivalence ratio. The tests were to be operated at an equivalence ratio of 1.38. The values listed in Table 1 are all higher, particularly in Test No. 50. The discrepancy stems from the additional fuel input through the slag tap torches and the inefficiency in combustion as reflected in carbon conversion. Typically, the air/fuel ratio is tracked and controlled during testing through the measured air and fuel inputs. The primary equivalence ratio is then calculated based on the measured O_2 concentration. Often a considerable discrepancy can exist between these two for the reasons sighted above.

The outlet temperature is dependent on the primary equivalence ratio and the coal loading of the fuel. This relation is illustrated in Figure 3. Graphed is outlet temperature versus equivalence ratio for the fuels with the three loadings. A trend of increasing coal loading producing increasing outlet temperature is shown. It should be noted that the data shown from Test No. 43 was taken while the combustor was operating without the slag tap heating torches. The remaining data was taken at a constant slag tap torch heat input. The influence of coal loading on outlet temperature is not large for the data taken with fuels of 50 and 54% coal loading.

The emissions are summarized in Table 1 and in Figure 4. The values in Table 1 are averaged over the entire test. Emissions of CO were below 15 ppmv @ 15% O_2 for all fuels tested. SO_2 emissions are a function of the sulfur loading of the fuel as nearly all the sulfur input into the combustor in the fuel is converted to SO_2 . Therefore, neither CO or SO_2 emissions are influenced by coal loading over this range of test conditions.

The emissions of NO_x are of greater interest relative to the influence of coal loading on combustor performance. Figure 4 is a graph of NO_x emissions versus equivalence ratio for the three different coal loadings. Interestingly, the lowest NO_x emissions are achieved with the fuel with the middle coal loading of 54%. Data is presented with this fuel taken in two tests. As mentioned above Test No. 43 was taken without the slag tap torches operating while in Test No. 48 the torches were in operation. The curve through these data suggest that the torches had no influence on NO_x emissions. The documented relation between NO_x emissions and equivalence ratio for the TSSC is illustrated by that curve plotted over data taken in Test Nos. 43 and 48. A typical NO_x emission signature would increase as the primary zone equivalence ratio is increased to a peak at 1.05. As the equivalence ratio is further increased the NO_x emissions fall off rapidly

Figure 3. Outlet Temperature Profile of TSSC Burning CWMs of Varying Coal Loadings

Figure 4. NO_x Emissions of TSSC Burning CWMs of Varying Coal Loadings

to a low at 1.25 to 1.35. The emissions slowly increase with further increases in equivalence ratio. The curve through data from Test Nos. 43 and 48 in Figure 4 illustrate this trend. The figure suggests that the highest NO_x emissions correspond to the lowest coal loading. This is not an expected result. Typically, as the water loading in the combustor is increased the flame temperature is decreased and correspondingly, so are the NO_x emissions. This trend is exhibited when considering the data presented from Test Nos. 43, 48, and 49. Here the NO_x emissions are increased as the coal loading is increased (and water loading is decreased). In light of the number of data points taken in Test No. 50, the data point taken at the lowest equivalence ratio could be errant and, in fact, if this data is viewed omitting that data point a convincing curve could be drawn corroborating the data from Test Nos. 43, 48, and 50.

The particulate samples indicate that the most efficient combustion was completed with "S3" the 58% coal fuel. The carbon conversion is the highest with that fuel at 99.7% and the particulate emissions are the lowest. CWM's "S1" and "S4" with lower coal loadings had worse carbon conversions at 97.2% for each. This trend can be explained by the higher water vapor concentrations in the primary zone combustor with fuels of decreasing coal loading. Higher water vapor concentrations lowers flame temperatures, which have a strong influence on system carbon conversion. The particulate emissions for tests with the low coal loading fuels was more than three times higher than Test No. 49. The particulate emissions include all unburned carbon and so carbon conversion and particulate emissions are strongly coupled. It should be noted that these data have been uncorrected for equivalence ratio which presents a problem in comparing the results. This is true more for the data taken in Test No. 50 in which the average equivalence ratio was 1.55. Typically, carbon conversion should decrease as primary equivalence ratio is increased past some critical value in the range of 1.5 to 1.75. However, this value has not been established for the TSSC.

The particulate ash and dilution water analyses are also included in Table 3 for the three tests. The ash analyses of the particulate usually reflect the ash composition of the coal burned. This trend is not reflected in the data presented in Table 3 in that Fe_2O_3 is the largest constituent for two of the tests (48 and 49) whereas in the coal ash SiO_2 is the major constituent. However, the three major constituents in the particulate ash analysis of Al_2O_3 , Fe_2O_3 , and SiO_2 are also the major constituents in the coal ash. The dilution water analysis indicates the presence of sulfur, metal ions from the ash, and dissolved alkalis.

The last combustor performance parameter is shown in Table 1 under the heading ash balance. The primary zone slag capture is the amount of coal ash separated by the impactor in the slagging combustor. In the TSSC the primary zone slag capture has varied from 10% to 85%. The combustor typically operates with a slag capture in the range of 55 to 70%. The values in Table 1 are substantially lower due to the reduced length of the primary zone. Typically, the primary zone is 24 inches from injector tip to impactor. In these tests the primary zone length was reduced to 16 inches. This reduction was necessary to accommodate the water quenched slag pit for on-line slag removal. In comparing results from these tests taken with varying coal loading the highest capture was achieved with the baseline fuel with the median coal loading. The accuracy of the slag capture is $\pm 10\%$ so determining any trend from the data in Table 1 is difficult. The data does suggest that the influence of coal loading on slag capture is not great.

Table 1 also includes the percentage ash emitted. This value is calculated from the particulate sample analysis. The primary zone slag capture and ash emission should balance to account

for all the slag put into the system. Unfortunately, two factors introduce error in this mass balance. First, in the TSSC without a PRIS a considerable portion of ash is frozen in the secondary combustor. Determining the amount of slag trapped in this region was not completed as it would have required a complete rig tear down. Secondly, the measurement of primary zone slag capture and ash emission are accurate to within only 10% so a potential 20% measurement error is present. The imbalance in the mass balance is included in Table 1 as both a percentage of the ash input and the weight of the unaccounted for ash. The worst data balance was obtained with the baseline fuel in Test No. 48. Determining a trend in slag capture with coal loading is not possible with the data presented.

In summary, three tests have been completed with CWMs of varying coal loadings from 50 to 58.2%. The TSSC was capable of utilizing all three fuel with little noticeable impact on combustor performance. The coal loading had a substantial impact on the fuel rheology with the CWM of highest loading being more difficult to handle. The emissions varied only slightly with NO_x emissions increasing with increasing coal loading. Combustor outlet temperature also increased with increasing coal loading. Carbon conversion was determined to increase slightly with increasing coal loading. The primary zone slag capture is not strongly influenced by coal loading.

Ash Concentration

The influence of coal ash on combustor performance has been investigated in three tests with CWMs "S1", "S6", and "S7" with coal ash loadings of 3.80, 8.84, and 12.81%, respectively. The properties of the three CWMs and the tests (Nos. 48, 51, and 52) they were used in are included in Table 16. The fuels were formulated to possess similar properties with the exception of coal ash loading. This goal was achieved to a large extent, but completely uncoupling changes to the ash loading from all the other CWM properties is not possible. In particular, heating value, volatile content, and fixed carbon all decrease with increasing coal ash concentration. The decrease of the latter two are a direct result of increased ash displacing volatiles and carbon. The heating value drops due to coal ash (without any heating value) displacing the carbon and volatiles (combustible). The composition of the ash does not vary significantly as the concentration in the coal is increased.

The combustor exhibited good operation with all three fuels. The combustor tests were operated at nearly identical conditions as listed in Table 1. Testing is completed in the subscale TSSC with the continuous slag removal system employing a water quench bath with a lock hopper in a conical primary zone combustor with the baseline injector configuration. The slag tap torches were operated continuously throughout all three tests. The operating parameters included in Table 1 are similar for the three tests.

The largest variation in test conditions was in primary zone equivalence ratio. The tests were to be operated at an equivalence ratio of 1.38. The discrepancy stems from the additional fuel input through the slag tap torches.

The operation of the combustor was similar in the three tests being discussed. The TSSC design is tolerant to a three-fold increase in coal ash concentration without any ill effects on combustor performance. In Test 52 with the highest ash loading more frequent adjustments to the rig back pressure valve were required. The back pressure valve is used to control the combustor pressure. Adjustments to this valve are required as air flow rate, gas temperature, particulate

loading, and quench water flow rate vary. During Test 52 (highest ash concentration) the increased adjustments to the valve were perceived to be caused by the increased ash emissions from the TSSC. Analysis of the particulate sample taken during that test do not support that perception because the particulate emissions were determined to be lower than in the other tests.

The outlet temperature measured in the three tests was uniform and nearly constant at an average near 1970°F as shown in Table 1. This trend is further illustrated in Figure 5, which is a plot of outlet temperature versus equivalence ratio for Tests 48, 51, and 52. The outlet temperature is measured at the exit of the secondary combustor. The table and figure indicate that coal ash concentration over the range of 3.7 to 12.8% has no influence on outlet temperature.

Emissions are summarized in Table 1 and in Figure 6. The values in Table 1 are averaged over the entire test. Emissions of CO were below 15 ppmv @ 15% O₂ for all fuels tested. SO₂ emissions are a function of the sulfur loading of the fuel as nearly all the sulfur input into the combustor in the fuel is converted to SO₂. Therefore, neither CO or SO₂ emissions are influenced by coal ash concentration over this range of test conditions. Likewise, the emissions of NO_x are not influenced by ash concentration. Figure 6 is a graph of NO_x emissions versus equivalence ratio for the three different coal ash concentrations. Test Nos. 48 and 43 were completed with the same CWM ("S1"), but in Test 43 the slag tap torches were not in operation. Figure 6 indicates that NO_x emissions are not influenced by coal ash concentration significantly. Data included from Test 43 shows the influence of the slag tap torches rather than the coal ash loading.

Figure 5. Variation of Outlet Temperature With Fuels of Varying Coal Ash Concentration

Figure 6. Variation of NO_x Emissions With Fuels of Varying Coal Ash

Post-test inspection of the combustor after each of the three tests revealed that as coal ash concentration is increased slag coatings and accumulations increase. In Test 48 the combustor was lightly coated with slag and little slag reached the water bath below the slag tap. After Tests 51 and 52 increasing slag accumulations were seen particularly below the slag tap. In both cases slag did not fully reach the water bath, rather froze/bridged across the insulation located between the slag tap and water bath. The amount of slag below the slag tap after each test was roughly proportional to the ash concentration of the CWM burned. The slag below the slag tap increased from 7.2, 16.5, and 45.4 lbs for Tests 48 (3.7%), 51 (8.8%), and 52 (12.8%), respectively. The secondary combustor had increasing slag accumulations with increasing ash concentration that were visually obvious.

The higher ash coal led to an apparent greater damage to the refractory. The casting in the combustor was reused for all three tests. The inner refractory used in the combustor is a high density alumina-silica castable - Thermal Ceramics Kaocrete HPM 90. The degradation of this material was noticeably escalated as the coal ash concentration was increased. The degradation was typical of the refractory damage observed after many tests completed with the TSSC. The refractory over a number of tests first, cracks, then pits, and finally erodes to the point where recasting is required. The higher ash loading did accelerate this damage. These tests illustrate that the amount of slag the refractory is exposed to has an influence on its life. Furthermore, these results suggest that the amount of slag may be the predominant factor controlling refractory life.

The particulate samples, included in Table 3, indicate that the most efficient combustion was completed burning "S7" with the highest coal ash. The carbon conversion is the highest with that fuel at 99.7% and the particulate emissions are the lowest. CWMs "S1" and "S6" with decreasing ash concentration exhibited decreasing carbon conversions at 99.0 and 97.2%, respectively. This trend suggests that coal ash actually improves combustion efficiency. One explanation of this measurement is that ash may act to break apart burning coal particles, so that, increasing coal ash results in greater coal fragmentation into finer coal particles during the combustion process. Finer coal particles would then be completely combusted in a significantly reduced residence time.

The particulate ash and dilution water analyses are also included in Table 3 for the three tests. The ash analyses of the particulate usually reflects the ash composition of the coal burned. This trend is reflected in the data presented in Table 3. The three major constituents in the particulate ash analysis of Al_2O_3 , Fe_2O_3 , and SiO_2 are also the major constituents in the coal ash. In Tests 51 and 52 these constituents are present in the same order of increasing concentrations for both the particulate and coal ash analyses. The dilution water analysis shows the presence of sulfur, metal ions from the ash, and dissolved alkalis.

The last combustor performance parameter is shown in Table 1 under the heading ash balance. The primary zone slag capture is the amount of coal ash separated by the impactor in the slagging combustor. In the TSSC the primary zone slag capture has varied from 10% to 85%. The combustor typically operates with a slag capture in the range of 55 to 70%. The values in Table 3-1 are substantially lower due to the reduced length of the primary zone. The accuracy of the slag capture measurement is $\pm 10\%$ for the low ash coal but improves as the ash concentration is increased. This improvement results from increased slag weight measurements relative to the accuracy of the scale, which are used to determine the slag capture. The data suggests that coal ash concentration improves primary zone slag capture.

The particulate emission measurements included in Table 1 support this conclusion that increasing coal ash concentration improves primary zone slag capture. This measurement shows the highest particulate emissions (2034 ppm) being measured with the baseline fuel that contains the lowest coal ash. In general, the higher the particulate emissions the lower the slag capture. This is obvious when considering an ash mass balance in the system. Ash not captured as slag in the primary zone is either emitted from the combustor in the form of particulate ash or frozen in the system between the primary zone and exhaust. In Tests 48, 51, and 52 the particulate emissions decrease with increasing coal ash concentration, which suggests that the slag capture should increase. Both the particulate measurements and the slag capture measurements support this observation.

The error in the mass balance is included in Table 1 as both a percentage of the ash input and the weight of the unaccounted for ash. The worst data balance was obtained with CWM "S6" with the medium ash level.

In summary, three tests have been completed with CWMs of varying coal ash concentrations from 3.7 to 12.8%. The TSSC was capable of utilizing all three fuels with little noticeable impact on combustor performance. The CWMs all exhibited similar handling properties. Gaseous emissions were not influenced by coal ash concentration. Carbon conversion was determined to increase with increasing coal ash concentration. The primary zone slag capture, although large measurement errors exist, did appear to improve as coal ash concentration was increased.

Higher coal ash resulted in faster refractory degradation and larger accumulations of slag in the secondary combustor.

No Additives

CWM "S5" was blended without the addition of the fuel additives normally included. The properties of this CWM are included in Table 16. This fuel contains no dispersant (A-23) or stabilizer (Flocon). Studies at Sandia Laboratory have found that these additives inhibit CWM atomization. By aiding the atomization process an improvement in combustion performance should be realized. The fuel also differs from the baseline CWM ("S1") in several other ways. The coal grind has a bimodal distribution, which is shown through an increased mean size. The coal loading is substantially lower than in the baseline with a resulting lower heating value. The CWM was intentionally blended with these properties as a potential hybrid CWM. The CWM was blended and shelved for approximately 10 months.

The operating conditions and major results for this test are included in Table 1. In Test 53 the combustor was operated at standard conditions with a slightly lower equivalence ratio. In general, the combustor exhibited below average performance. In particular, the CO emissions were higher and the slag capture was substantially lower. Another indication of poor combustor performance was the large amount of char found in the water bath after the test. While mixing the CWM, a thick "gelatin" like quality was noted. The thickened fuel caused a higher than normal fuel pump pressure and eventually led to a clog in the CWM delivery line upstream of the mass flowmeter. The clog forced an early shut-down of the test.

The thickened appearance of the CWM is not supported by the viscosity measurements made after the fuel was prepared. In Table 16 a viscosity of 375 cp @ 100/sec is listed. While this value is slightly higher than the typical specification of 300 cp, the viscosity measurement does not corroborate with the CWM "gelatinous" appearance. Without the addition of an antibacterial agent the CWM may have been altered biologically while sitting for the past 10 months, but tests of the CWM showed no abnormalities.

The particulate sample taken in this test has been analyzed and data is included in Table 1 and 3. The carbon conversion is in-line with other tests and the particulate emissions are slightly improved. These results are slightly contradictory to the above statements that the combustor exhibited poorer performance than other tests.

In conclusion, a CWM with no additives has been tested and exhibited poorer combustion performance. The CWM appeared to be substantially thicker than other fuels tested leading to a clog in the fuel delivery line.

Coal Particle Size

The influence of coal particle size on combustor performance has been investigated in three tests with CWMs "S1", "S8", and "S9" with coal particle top-sizes of 45, 25, and 75 microns, respectively. The properties of the three CWMs and the tests (Nos. 48, 54, and 55) they were used in are included in Table 16. The fuels were formulated to possess similar properties with the exception of coal particle size. This goal was achieved to a large extent.

The combustor exhibited good operation with all three fuels. The combustor tests were operated at nearly identical conditions as listed in Table 1. The operating parameters included in Table 2 are similar for the three tests.

The largest variation in test conditions was in primary zone equivalence ratio. The tests were to be operated at an equivalence ratio of 1.38. The discrepancy stems from the additional fuel input through the slag tap torches.

The operation of the combustor was similar in the three tests being discussed. The TSSC design is tolerant to a three-fold increase in coal particle top-size without any ill effects on combustor performance. Test 55 was a slightly smoother test than either of the other tests in terms of combustor outlet temperature and pressure and the need for back pressure valve adjustment. The back pressure valve is used to control the combustor pressure. Adjustments to this valve are required as air flow rate, gas temperature, particulate loading, and quench water flow rate vary.

The outlet temperature measured in the three tests was fairly uniform at an average of 2000°F as shown in Table 1. This trend is further illustrated in Figure 7, which is a plot of outlet temperature versus equivalence ratio for Tests 48, 54, and 55. The outlet temperature is measured at the exit of the secondary combustor. The table and figure indicate that coal particle top-size over a range of 25 to 75 microns has no detectable influence on outlet temperature over a variation of primary equivalence ratio of 1.3 to 1.7.

Figure 7. Outlet Temperature and Emission Characteristics of TSSC Burning CWMs Made From Coals of Varying Particle Size

Emissions are summarized in Table 1 and in Figure 7. The values in Table 1 are averaged over the entire test. Emissions of CO were below 20 ppmv @ 15% O₂ for all fuels tested. SO₂ emissions are a function of the sulfur loading of the fuel as nearly all the sulfur input into the combustor in the fuel is converted to SO₂. Therefore, neither CO or SO₂ emissions are influenced by coal particle size over this range of test conditions. Figure 7 is a graph of NO_x emissions versus equivalence ratio for the three different coal particle sizes. Figure 7 indicates that NO_x emissions are not influenced by coal particle size significantly.

Post-test inspection of the combustor after each of the three tests revealed that coal particle top-size variations of 25 to 75 microns has no noticeable impact on slag coatings and accumulations. In the three tests being compared the combustor was lightly coated with slag and little slag reached the water bath below the slag tap. Accumulations of slag in the secondary combustor were light.

Analysis of particulate samples have been completed to provide the carbon conversion and particulate emissions data included in Table 1. The analysis of the three samples is included in Table 3. The particulate samples indicate that the most efficient combustion was completed burning "S9" with the largest coal particle top-size. The carbon conversion with that fuel is the highest at 98.5% and the particulate emissions are the lowest. CWM's "S1" and "S8" with consecutively finer grinds exhibited carbon conversions of 97.2 and 97.9%, respectively. The data does not show a distinct trend with coal particle size. Given the small variations in carbon conversion these results may reflect measurement errors. An alternative explanation assuming that the carbon conversion does vary as indicated may come from an examination of the atomization process. It has been surmised that CWM atomization is improved by a mix of small and large particles, rather than all small particles. If a mix of large and small particles can be atomized more finely than a fluid containing only small particles then the carbon conversion should trend with the size of the droplets generated rather than the size of the coal particles.

The particulate ash and dilution water analyses are also included in Table 3 for the three tests. The ash analyses of the particulate usually reflect the ash composition of the coal burned. This trend is reflected in the data presented in Table 3. The three major constituents in the particulate ash analysis of Al₂O₃, Fe₂O₃, and SiO₂ are also the major constituents in the coal ash. In Tests 54 and 55 these constituents are present in the same order of increasing concentrations for both the particulate and coal ash analyses. The dilution water analysis shows the presence of sulfur, metal ions from the ash, and dissolved alkalis.

In comparing ash balance results from these tests taken with varying coal particle size the highest slag capture was achieved with the CWM of a medium coal grind (45 microns). The accuracy of the slag capture measurement is $\pm 10\%$ for the CWM's tested. Both the fine and coarse coal grinds had similar slag capture efficiencies. The decrease in slag capture with either increasing or decreasing coal particle size from 45 microns is not fully understood. Measurement error could certainly contribute to these findings. This result can also be explained by the influence of particle size on atomization as discussed in the previous section.

In summary, three tests have been completed with CWMs of varying coal particle top-size of 25 to 75 microns. The TSSC was capable of utilizing all three fuels with little noticeable impact on combustor performance. The CWMs all exhibited similar handling properties. Gaseous emissions were not influenced by coal particle size. Carbon conversion is only weakly influenced by coal

particle size with the highest conversion obtained with the largest top-size. The primary zone slag capture, although large measurement errors exist, did appear to get worse as coal particle top-size was increased or decreased from 45 microns.

Coal Seams

The difference in combustor performance with CWM's made from four different coal seams has been investigated in four tests with CWMs "S1", "S10", "S11", and "S12". These mixtures have been produced from coals taken from the Kentucky 4A/Elkhorn, Upper Freeport, Soldier Creek, and Illinois No. 6. seams, respectively. These seams are potential sources of coal for the coal-fueled Centaur sited in different regions of the country. The properties of the four CWMs and the tests (Nos. 48, 56, 57, and 58) they were used in are included in Table 16. The fuels were formulated to possess similar properties with the exception of the coal seam used to produce the slurry. The coal seam has a substantial impact on fuel properties. In particular, these seams show significant variations in volatile content and ash loading. A more complete comparison of the fuels is included in Section 5.2.

The combustor exhibited good operation with all four fuels. The combustor tests were operated at nearly identical conditions as listed in Table 1. The operation of the combustor was similar in the four tests being discussed. The TSSC design is capable of utilizing bituminous coals from different coal seams located in different regions of the country. The principle differences in operation of the combustor with these fuels occurred in Tests 56 and 58. In Test 56 the back pressure valve required more frequent purges. With CWM "S10" the increased ash loading of the coal lead to the increased number of purges. During Test 58 the fuel exhibited poorer fuel pumping characteristics with variations of plus/minus 7.6%. Analysis of the fuel sampled at the combustor inlet has indicated rather standard properties. The fuel pump has operated normally in subsequent tests. A heavier build-up in the fuel filters was noted at the conclusion of Test 58. This blockage is the probable cause of the fluctuations in the fuel flow rate. A more robust feed system could be designed to adequately deliver CWM "S12".

The outlet temperature measured in the four tests was fairly uniform at an average of 1979°F as shown in Table 1. This trend is further illustrated in Figure 8, which is a plot of outlet temperature versus equivalence ratio for Tests 48, 56, 57, and 58. The outlet temperature is measured at the exit of the secondary combustor. The table and figure indicate that the coal seam has little influence on outlet temperature. The highest temperatures on average resulted from the Upper Freeport coal which has a medium volatile content of 25.8% versus 35 to 39% for the other coals. This coal also exhibited the highest carbon conversion at 99.8% which should result in a higher outlet temperature.

Emissions are summarized in Table 1 and in Figure 8. The values in Table 1 are averaged over the entire test. Emissions of CO were below 25 ppmv @ 15% O₂ for all fuels tested. SO₂ emissions are a function of the sulfur loading of the fuel as nearly all the sulfur input into the combustor in the fuel is converted to SO₂. Therefore, neither CO or SO₂ emissions are influenced significantly by coals taken from different coal seams. Likewise, the emissions of NO_x are not influenced by these coals from different bituminous seams. Figure 8 is a graph of NO_x emissions versus equivalence ratio for the four different coal seams. Figure 8 indicates that NO_x emissions are not influenced by coals from different seams significantly.

Figure 8. Outlet Temperature and Emission Characteristics of TSSC Burning CWMs Made From Coals From Different Seams

Post-test inspection of the combustor after each of the four tests revealed that the slag coatings are a strong function of the ash content of the coal. Tests 48, 57, and 58 all had light coatings on the primary zone wall and in the secondary combustor, while in Test 56 the slag coatings and accumulations are heavier particularly in the secondary combustor. In Test 58 a greater slag capture in the primary zone was demonstrated.

The particulate sample analyses in Table 3 indicate that the most efficient combustion was completed burning "S10" from the Upper Freeport seam. The carbon conversion is the highest with that fuel at 99.8% and the particulate emissions are the lowest. The CWMs made from the coals from the different coal seams all burned with carbon conversions above 98%, higher than the baseline coal at 97.2%.

The particulate ash and dilution water analyses are also included in Table 3 for the three tests. These data show typical trends of the ash composition reflecting the composition of the particulate ash.

Comparing ash balance results presented in Table 1 from these tests taken with coals from different seams the highest slag capture was achieved with the coal from the Illinois No. 6. The accuracy of the slag capture measurement is $\pm 10\%$ for the CWM's tested. The other seams demonstrated slag captures ranging from 23 to 37%. The slag capture values reported in Table 1 trend most significantly with the Fe_2O_3 content of the coal ash. Iron oxide has been found to reduce slag viscosity at constant temperature in reducing environments. In these tests where the Fe_2O_3 content varied from 20.08% (S12), 12.12% (S1), 11.92% (S10), to 7.67% (S11) the slag captures varied from 54%, 37.2%, 31%, to 23%, respectively. The primary zone slag capture and ash emission should balance to account for all the slag put into the system. The error in the mass balance is included in Table 2 as both a percentage of the ash input and the weight of the unaccounted for ash. The worst data balance was obtained with CWMs "S10" and "S11".

In summary, four tests have been completed with CWMs made from coals from different coal seams. The coal seams used are a Kentucky 4A/Elkhorn blend, Upper Freeport, Soldier Creek, and Illinois No. 6. All four seams are bituminous coals that potentially will be supplies for the Coal-Fueled Centaur as it is sited in different regions of the country. The TSSC was capable of utilizing all four fuels with little noticeable impact on combustor performance. The CWMs exhibited similar handling properties except for the slurry from the Illinois No. 6 seam which was more difficult to pump. Gaseous emissions were not influenced by the coal seam. The highest carbon conversion was obtained with the coal from the Upper Freeport seam which has the lowest volatile content. The primary zone slag capture, although large measurement errors exist, was highest with the Illinois No. 6, which had the highest Iron content in the ash.

Coal Fuel Specification

Testing conducted in the TSSC to study the influence of fuel properties on combustor performance has been completed to design a fuel specification for the F/S combustor. The design goal of the TSSC is to make a system that could use an extremely large range of fuel properties. The test results indicate that the design goal has been met.

Testing has indicated that the combustor can efficiently burn slurries with coal loadings ranging from 49.9 to 58.2%, ash content of 3.8 to 12.8%, coal particle top-size of 25 to 75 microns, and bituminous coals from a large number of seams located regionally in the U.S. The tests have indicated that only high coal loading and CWMs formulated without any additives severely impact the combustor performance. Fuels lth high coal ash lead ot faster refractory damage, but do not impact combustor prformance while the refractory is intact.

Based on these test rsults and all earlier tests, the fuel specification for full scale combustor testing has been set and is included in Table 15. These fuel properties do not represent limits for ash concentraltion, coal loading, etc., but are hte fuel properties that have consistently yielded the best system performance results. The fuel specification for the coal-fueled engine has not yet been fully determined. with the results obtained in this study, it is known that the combustor can be fueled with a considerably broader range of CWM properties than have been used in the past.

3.2.2 Full Scale Combustor Testing

Testing of the full scale combustor is being completed independently of the engine at the Caterpillar Technical Center in Peoria, Ill. The entire combustor island which includes the primary combustor, PRIS, and secondary combustor installed together as illustrated in Figure 9 will be tested later in this test series. The first series of tests are being completed without the PRIS. The test set-up including the primary and secondary combustors installed at the Tech Center are included in Figure 10 as a photograph and in schematic form in Figure 11.

The facility is capable of providing 25.0 pps of air flow preheated to 605°F and an additional 2.6 pps of unheated (but higher pressure) air for atomization. The facility is capable of 31 pps air delivery. The combustor will be operated at 7.0 atmospheres rather than the Centaur operating pressure of 10.0 atmospheres due to the air supply limitations. The Centaur Type H uses 39.8 pps of total air flow. The combustor hardware will be instrumented for temperature, pressure, and emission measurements using standard techniques and commercially available equipment.

Figure 9. Combustor Island

Figure 10. Test Set-Up at Caterpillar Tech Center

Figure 11. Full-Scale Combustor Without PRIS

The operation and performance of the combustors will be evaluated in a series of seven combustion tests. In these tests the combustor island will be operated on diesel fuel for a 4 to 6 hour warm-up period. Refractory wall temperatures measured 1.0 inch from the inner surface of the primary combustor are monitored. When these temperatures reach 2000°F the combustor is switched from diesel to CWM. Upon switching to CWM all diesel fuel flow is terminated. The combustor island is operated burning CWM for 4 to 6 hours at steady conditions. These conditions are a pressure of 7 atmospheres, primary zone equivalence ratio of 1.38, air inlet temperature of 605°F, and a combustor pressure drop ratio of 4%.

When the PRIS is installed, the inlet temperature to the PRIS is monitored and not allowed to exceed 2950°F so as to protect the ceramic rods. This temperature is controlled by increasing or decreasing the primary zone equivalence ratio. If a major adjustment to the equivalence ratio is necessary the primary to secondary air flow split will be changed between tests so that the

outlet temperature of the combustor can be maintained at 1900°F. At the conclusion of the CWM test the combustor is switched over to diesel fuel again for a cool-down of 2 hours.

During operation on CWM data is taken at approximate twenty minute intervals. Along with the operational data a complete temperature and pressure map will be recorded as well as gaseous emissions and particulate samples. At the conclusion of the test after the combustor has cooled the slag capture efficiency will be determined by measuring the quantity of slag captured in the slag pits. This measurement can be checked against the ash emission rate as determined from the particulate sample. The combustor is also inspected for slag accumulations and refractory damage.

The full scale combustor has been operated in four tests without the PRIS in-line. The tests were completed to cure the refractory, shakedown the test facility burning diesel fuel, and demonstrate CWM combustion. During the initial CWM combustion test data was obtained so that the primary to secondary flow split can be adjusted. These objectives were accomplished in Test Nos. 1, 2, and 4. Operating conditions and results from all full scale tests are included in Table 4. In addition, Table 4 includes the design point operating conditions.

Test 1

The first test was ended after 21 hours of operation with hot air flowing through the combustor. The heat-up schedule is included on the graph in Figure 12. Heat-up on air up to 730°F went very well over the first 16 hours. A series of difficulties with the diesel delivery system were encountered and corrected during the test over a four hour period. After completing these fixes the diesel torch was lit on the first attempt. Light-off on diesel fuel in the combustor was completed within the next ten minutes. Flange leaks in the exhaust piping upstream of the back pressure valve were observed as the quench water was increased. Significant amounts of steam venting into the test cell forced rig shut-down. Other system and test problems have been identified and were corrected.

Temperature records are the only data recorded for this test. As the graph indicates the air temperature was kept close to plan. The curing schedule was designed to maximize refractory life.

Test 2

The objective of Test No. 2 was to complete the refractory curing schedule and burn diesel at test pressures up to 87.5 psig. One hour operation with CWM was planned upon successful completion of the diesel test.

The air temperature was ramped up to 730°F over nine hours to drive out moisture from the refractory and bring up the refractory temperature. A temperature-time history of the test is included in Figure 13. The air temperature was dropped down to 620°F in preparation for diesel combustion. The torch was ignited and light-off on diesel fuel completed within ten minutes. Temperatures of the refractory ("pluses") and gases ("triangles") exiting the primary zone are included in the graph. The primary air/fuel ratio was started at 30 and decreased over three hours to 24. The pressure in the combustor was maintained at 40 psig throughout the test. The plan to increase the pressure to 87.5 psig could not be completed due to inaccurate air flow

Table 4. Full Scale Combustor Test Results

Test No.	Design	1	2	3	4
Objective	-	Curing	DF No.2	1st CWM	1st CWM
Main Fuel	CWM	-	Diesel	Diesel	CWM "W"
T _{in} (°F)	620	400-730	616	610	605
P _{in} (psig)	132.2	0-23	41.	43.8	61.5
$\phi_{primary}$	1.38	-	.49-.61	.59	1.33
$\Delta P/P$ (%)	4.0	-	4.07	4.20	4.0-3.2
Heat (MMBtu/hr)	47.5	-	11.3	11.5	44.8
T _{primary} (°F)	2900	730	2827	2751	2846
T _{secondary} (°F)	1900	695	1441	1363	1967
RESULTS					
Emissions @ 15%					
NO _x (ppmv)	125	-	-	212.4	52.1
[lbm/MMBtu]				[2.289]	[0.245]
CO (ppmv)	50	-	-	0	31.4
[lbm/MMBtu]					[0.044]
SO ₂ (ppmv)	75	-	-	27.5	171.0
[lbm/MMBtu]	w/Sorbent			[0.413]	[1.134]
w/o Sorbent					
Part. (ppmm)	120	-	-	-	N/A
Carbon Conv. (%)	98	-	-	-	N/A

measurements in the cold run of the air supply. As the figure indicates gas temperatures up to 2795°F were recorded with refractory temperatures up to 2375°F. Provisions for switching to CWM were made, but after 3 hours burning diesel fuel a leak was noted in the exhaust duct downstream of the back pressure valve.

The combustor was inspected with a borescope and was found to be in excellent shape. All refractory was in "as cast" shape with only a few small cracks noted in the refractory around the injectors.

Figure 12. The Temperature History of the Full-Scale Combustor During the First Refractory Curing Diesel Test

Figure 13. Temperature-Time History of F/S Combustor During Test No. 2

The temperature history of the test is attached. This test has successfully completed the refractory curing process and demonstrated combustion of diesel fuel. The combustor operated smoothly with outlet temperatures reaching 1442°F. The refractory heated faster than anticipated with less heat loss than in the subscale combustor. The primary zone gas temperature of 2800°F at an air/fuel ratio of 24 indicates that the heat loss has been lowered over the subscale combustor. In the subscale combustor the primary zone temperature typically is on the order of 2900°F at an air/fuel of 20. Skin temperatures of the combustor remained below 230°F as determined by an infra-red temperature gun.

As indicated in Table 4, the primary to secondary air flow split during the test was below design at 1.6 versus 2.8. The gap in the CWM injectors for metering primary air is oversized by approximately 30% and the secondary air supply piping is undersized. A plate with a 4.33 inch bore was installed in the primary air supply leg to increase the flow split. This was a temporary solution so that the next test could be completed. To correct the problem permanently the gap on the fuel injectors must be reduced. This procedure should not be completed until the combustor is operated burning CWM.

Test Nos. 3 and 4

The next two tests were completed to demonstrate CWM combustion for the first time. Flow data through the system while burning CWM were obtained so that the secondary to primary flow split could be adjusted. In addition, other preliminary CWM combustor performance data were obtained. Results from these tests are summarized in Table 4.

In Test 3 difficulties with the higher pressure water pump required to quench the exhaust precluded completing transfer to CWM. The air temperature was ramped up to 600°F and rig pressure increased to 40 psig. Light-off on DF#2 was accomplished readily. A total of 4283 lbs of diesel were burned over 5.5 hours. The rig pressure was ramped to 60 psig and the A/F in the primary zone was decreased to 23. Emissions were measured at one point. The primary zone equivalence ratio was 0.58 indicating fuel lean combustion. The outlet temperature reached a maximum of 1363°F. The primary exhaust reached 2751°F. Refractory temperatures in the primary zone reached 2548°F with an average of 1904°F.

Test 4 was the second test completed to demonstrate CWM combustion. This test was completed with 2.5 hours of CWM combustion completed. Used in this test was CWM "W". The specifications of this fuel are included in Appendix A. The fuel has "baseline" specifications and is described in greater detail in Section 5.

During the test, the air temperature was ramped up to 600°F and rig pressure increased to 40 psig. Light-off on DF#2 was accomplished readily. The rig pressure was ramped to 60 psig and the A/F in the primary zone was decreased to 23. The primary zone outlet temperature reached 2660°F on DF#2 with a secondary outlet up to 1315°F. Transfer to CWM was completed swiftly and the diesel fuel was shut-off rapidly. The combustor ran very smoothly on CWM. The back pressure valve was fully open after operating on CWM for only several minutes. The primary zone $\Delta P/P$ started at 4% and dropped during the 2.5 hour test to 3.2. The flow split averaged 2.33 pps of secondary air for each pps of primary air. A temperature-time history of this test is included in Figure 14. This figure includes temperature data from the slag pit, impactor walls, secondary combustor outlet, primary walls and the primary outlet. Figure 14 also contains the

variation of $\Delta P/P$ during the test. The average outlet temperature was 1967°F. The primary outlet reached 2846°F and averaged 2787°F. The impactor area leading into the slag tap climbed throughout the test to 2174°F, while the slag pit remained relatively cool with a 480°F maximum. CWM was stopped when a crack developed in the bellows connecting the secondary air supply pipe with the secondary air manifold. The rig was transferred back to diesel and operated an additional 0.5 hours before cool down.

Emissions were measured five times during the test and this data is included in Figure 15. This figure is a graph of NO_x , CO, secondary outlet, and primary outlet temperature versus primary zone equivalence ratio. The primary zone equivalence ratio averaged to 1.33, but due to the drop in $\Delta P/P$ fell from 1.44 to 1.13 during the test. The emissions indicate good combustion with NO_x below 53 ppmv and CO below 31.4 ppmv. The CO emissions rose from 18 to 49 ppmv throughout the test while the NO_x dropped from 68 to 40 ppmv. The trends of these pollutants with equivalence ratio are contrary to results obtained in subscale testing. Typically, NO_x emission levels increase while CO emissions drop as the equivalence ratio is increased from stoichiometric (1.0) to design point (1.38). The results can be explained as an indication of a drop in combustion efficiency most likely resulting from the decreasing $\Delta P/P$. The primary and secondary outlet temperatures graphed versus equivalence ratio show the expected trends. A particulate sample taken during the test is being analyzed.

Post-test inspection of the combustor indicated some refractory problems. Most notably the impactor has broken along one edge as shown in the photograph of Figure 16. The reason the impactor has broken is believed to be insufficient support of the free hanging refractory. The impactor is supported by four refractory "ribs" resulting in a free hanging distance of over ten inches. The plan is to increase the number of support ribs to six. In addition, subscale development of a water-cooled impactor is being pursued.

The remaining refractory is coated with a relatively even coating of slag. Some spalling of the refractory is indicated in Figure 17. The injectors are in good shape, but the refractory surrounding them is already showing wear as can be seen in Figure 18. The secondary combustor, pictured in Figure 19, is showing significant slag accumulations, particularly around the secondary air nozzles. Such accumulations have been observed in subscale testing without the PRIS and were anticipated. The slag capture could not be determined because of the new refractory which tends to "soak-up" slag. No slag accumulations reached below the impactor and into the slag pit.

Figure 14. The Temperature-Time History of the Full-Size Combustor at Several Locations for Test No. 4

Figure 15. The Variation of Emissions and Outlet Temperature Versus Equivalence Ratio for Test No. 4

Figure 16. The Impactor Top After Test No. 4

Figure 17. Refractory Spalling on the Primary Zone Walls Following Test No. 4

Figure 18. The CWM Injector Following Test No. 4

Figure 19. A Downstream View of the Secondary Combustor With Slag Accumulations at the Secondary Air Inlet Ports. Emission Probes are Visible Further Downstream.

4. PHASE II - TASK 2 - PARTICULATE REMOVAL SYSTEM DEVELOPMENT

4.1 SPECIFIC ITEMS OF PROGRESS

4.1.1 Post-Primary System

- Analysis of the silicon carbide PRIS tubes exposed to CWM combustion in all tests before IBSTF No. 9 has been completed. The tubes have been degraded by reactions of iron from the coal ash with silica from the PRIS tubes to form an iron silicate that is easily eroded.
- The subscale PRIS with alumina rods has been in position during all testing since IBSTF No. 9. Included is a sample section located upstream of PRIS inlet which has test pieces of alternate PRIS rod materials including Lanxide, mullite, silicon carbide, zirconia, and cordierite.
- The full scale PRIS design has been completed. A full size flow visualization model has been operated demonstrating a low pressure loss and high slag capture. The data from the model has been used to modify the PRIS rod section and the slag tap area. Fabrication of the full size PRIS vessel has been completed for all sections except the rod spool. This section cannot be completed until the PRIS rod material is selected after evaluation of the sample pieces following the next 50 hour IBSTF test.

4.1.2 Post-Secondary System

- One of the two failed candles was examined by four point bend testing, X-ray diffraction, and scanning electron microscopy with EDAX.
- Resonant frequency data was collected for a new Schumacher candle as well as an exposed candle.
- Conducted frequency measurements of Schumacher candle filter in the Hot End Simulation Rig.
- A venturi scrubber system was commissioned at the IBSTF in order to meet the County of San Diego particulate requirements.
- Candles were ordered and received from Industrial Filter and Pump Manufacturing Company.
- Four filtration consultants were interviewed and Owen Fortune was subcontracted as a filtration expert.

- Several runs with diesel fuel and three runs with coal were conducted on the IBSTF.
- Kistler pressure transducer measurements were taken in the IBSTF with diesel firing. Pressure fluctuations were ± 0.1 psid in general, with occasional spikes of ± 1 psid.
- All Industrial Filter and Pump candles have been boroscoped on the inside. Data was recorded on video tape and aberrations noted in the records.
- All candles were visually inspected, weighed, and physical dimensions noted.
- New candle mounting gaskets were manufactured.
- A test-rig apparatus was fabricated for vibration testing of the Industrial Filter and Pump candles.
- A long-term vibration test was initiated to determine the effects of local vibrations on the strength of the candles. Two new Schumacher candles have been used for this test.
- Full scale cost estimates were developed for Solar by Industrial Filter and Pump Manufacturing Company.
- A lean PRIS analysis was begun. Arthur Metcalfe was hired as an expert consultant.
- A two part report on the analysis of the lean PRIS was compiled for Solar by Arthur Metcalfe and Associates. The first part of the report comprised the analysis of the operating conditions whereas the second part discussed factors affecting the selection of additives. Additional work has examined removal of sticky deposits.

4.2 DISCUSSION

4.2.1 Primary Cleanup Device

Subscale PRIS

Analysis of the silicon carbide rods removed after Test No. 9 is complete. An SEM photograph of the slag rod interface is included in Figure 20. In the photograph the interface between the slag and the silicon carbide has been divided into four regions (a) to (d). A piece of the rod covered with slag has been sectioned and polished for the SEM analyses included with the photograph in Figure 20. Region (a) is the uncorroded silicon carbide PRIS rod. The SEM analysis indicates high levels of silica. In region (d) is the pure slag with high levels of alumina and silica. The iron from the slag reacts with the silicon of the rods to create an iron silicate as shown in regions (b) and (c). The iron silicate created by the interaction of the slag with the iron has a fairly low

Figure 20. SEM Analysis of PRIS Rods After IBSTF Test No 9

softening point. With the gas and particle velocities found throughout the PRIS rods the iron silicate is rapidly eroded off the rod surface. "Fresh" silicon carbide is exposed to slag and the reaction to iron silicate continues as more material is lost from the rods.

The SEM analysis does not indicate a large alkali presence in any region shown in Figure 20. The lack of alkali precludes the likelihood of significant corrosion resulting from alkali attack. The presence of water vapor has been found to enhance corrosive reactions, particularly in the presence of alkali metals. The role water vapor plays in the iron-silica reactions occurring on the PRIS rods is not well defined, but should not be precluded as a possible aid in the corrosion process.

The subscale PRIS is being prepared for the next long duration IBSTF test. The PRIS has been exposed to combustion in three IBSTF tests. The rod-type insert with high purity alumina rods has been installed in the pressure vessel. The alumina rod PRIS inlet and outlet are included as photographs in Figures 21 and 22, respectively. Sample rods of Lanxide, mullite, silicon carbide, zirconia, and cordierite have also been installed in the cavity upstream of the insert for exposure in the next test. A photograph of the rods are included in Figure 23. These rods are cast at one end only and examined after testing for hot corrosion or erosion. The rod types and dimensions are summarized in Table 5.

These rods have been cast in a refractory base that will fit in the cavity upstream of the PRIS inlet as shown in Figure 24. The base has been before installation was completed.

Figure 21. Alumina Rod PRIS Inlet

Figure 22. Alumina Rod PRIS Outlet

Figure 23. PRIS Subscale Rod Material Cast In Support for Mounting In the IBSTF

**Table 5. Sample PRIS Rods to be Evaluated for Hot Corrosion/Erosion
In IBSTF Test No. 10**

<u>Material</u>	<u>Shape</u>	<u>Dimensions</u>
I-Zirconia 690	Tube	11/16 in. OD X 7/16 in. ID X 6 in. LG
I-Mullite 980	Tube	1.25 in. OD X 7/8 in. ID X 6 in. LG
I-Mullite 900	Tube	1.25 in. OD X 3/4 in. ID X 6 in. LG
I-Corderite 995	Tube	1.25 in. OD X 3/4 in. ID X 6 in. LG
Lanxide 90-x-060	Tube	1.0 in. OD X 0.775 in. ID X 6 in. LG
SIC - Hexoloy	Tube	1.0 in. OD X 1/2 in. ID X 6 in. LG

**Figure 24. Sample PRIS Rods Mounted In IBSTF Upstream
of Alumina Rod Insert**

Full Scale PRIS

The full scale flow visualization model has been fabricated and is pictured in Figure 25. The model has been tested with helium bubbles to trace the aerodynamic streamlines. These tests have indicated that flow through the rods and the duct downstream are uniformly distributed across the radius. As the air travels downstream of the PRIS rods it maintains a uniform profile until it nears the exhaust duct where it rapidly contracts towards the exhaust. The flow around the slag tap is light.

The model has also been operated injecting honey into the inlet to simulate slag and predict slag capture and flow characteristics. The results indicate that the PRIS captures 98+% of the honey. The honey flows down the rods and along the bottom of the PRIS duct in a stream. The slag tap area of the model has been modified to improve slag flow through this region.

The full scale PRIS design has been completed. The design is shown in Figure 26. The design has been modified to decrease the pressure drop across the device. Cold flow pressure drop measurements taken with the flow visualization model have been made at representative flow rates. These measurements indicate that the pressure drop across the PRIS will be approximately 1%. The full scale PRIS design is based on a first row velocity of 300 ft/sec. The

Figure 25. Full-Scale PRIS Model

PD01176

Figure 26. The Full-Scale PRIS Design

subscale PRIS was designed with this design criterion, but actually tested at a lower velocity of 235 ft/sec. In light of the high slag removal rate of the subscale PRIS, the full scale PRIS design is being modified to establish a velocity at the first row of rods of 235 ft/sec. The PRIS inlet diameter is being increased from 15 to 16 inches with an additional rod being placed in each of the first four rows. The outlet diameter of the PRIS will remain at 21 inches. The pressure drop of 1% will be improved further with the modified PRIS design with the reduced velocities.

The full scale PRIS design details were sent to Cascade Mechanical in Spring Valley, CA and fabrication of all vessel components have been complete with the exception of the final casting in the rod spool. This casting will not be completed until the material selection for the rods is made. This selection will be based largely on the results of the next IBSTF duration test. Photographs of the PRIS vessels are included in Figures 27 and 28.

4.2.2 Post-Secondary Systems

Testing

A fifty hour test was conducted in 1990 in which two candle filters failed during operation. An failure analysis was conducted and is reported here. The background of the test follows.

The two failed candles were not adjacent. Thus, one candle did not, upon failure, strike another candle, causing it to fail. A diagram of the proximity of the two failed candles to the inlet gas is shown in Figure 29. One of the candles was on the perimeter nearest the inlet; the other was diametrically opposite and also on the perimeter. It should be noted that 71% of the candles were

Figure 27. Full-Size PRIS Components Unassembled

Figure 28. Full-Size PRIS Slag Removal Section

Figure 29. Location of Candle Failures During Extended Tests

mounted on the perimeter. Thus, the probability that if two candles failed happened to be on the perimeter is 49.5 percent, assuming location had no effect.

It is noteworthy that both failures occurred about within seven inches of the top flange. A summary of the location on the candle where breakages have been observed is noted in Table 6.

Analysis of Failed Candles

An analysis of failed candles was initiated to determine what causes were responsible for the breakages. This analysis included drawing up a fault tree for the analysis, analysis of one of the broken candles, and also, examining the various possible causes. The analysis of one of the two failed candles was undertaken by Acurex Corporation. Additional testing of exposed candles is planned under a future subcontract with Acurex.

The fault tree analysis is shown in Figure 30.

Acurex Corporation examined one of the two failed candles from the extended test. Earlier, Acurex examined three virgin candles from the same batch. The approach included visual examination, scanning electron microscopy with Energy Dispersive Spectroscopy (SEM/EDX), X-Ray Diffraction (XRD) and four-point bend testing. Examination of unused filters provided baseline data for comparison.

Table 6. Summary of Location of Candle Breakages

Date	Location (Inches from top flange)	Occurrence
18 April 90	5.5	Earthquake
18 April 90	5.6	Earthquake
10 May 90	7.0	Extended test
10 May 90	7.0	Extended test
April '90	5.25	Handling
May '90	6.75	During removal
KRW Gasifier		(mechanically casued failures)
	6.5	
	5.375	
	5.0	
	5.5	
	5.75	
	9.25	
	8.25	

The candle that was received by Acurex was in several pieces, although essentially all the pieces were recovered so that it was possible to reconstruct it. Both sides of the cracked surface were examined. Examination of the top part of the candle revealed two holes, shown here in Figures 31 and 32. One hole was quite large (approximately 3 mm) and extended from the inside surface approximately 10 mm towards the outside surface. The second hole was much smaller and irregularly shaped, but extended completely through the candle. The crack ran through both of these holes. The smaller hole also showed evidence of dust penetration, indicating that there was flow through this hole before the candle broke.

Four-point bend data were obtained for the failed candle as well as three unused specimens. There was a significant decrease in strength. The degradation was so pronounced that after cutting bars for the bend test, the material appeared to be very weak and crumbly to the touch. In fact, the first set of bars failed prematurely; therefore, a different technique was used for surface preparation. The second set of bars had a finish ground to one micron. These specimens produced more consistent results. Test results for the unused and exposed samples are shown in Table 7 and Figure 33.

Figure 30. Candle Failure Analysis Tree

Figure 31. Imperfections in Candle Wall

Figure 32. Hole Through Candle Wall (from Interior of candle)

Table 7. Four-point Bend Test Data for Candle Specimens

Sample	MPa Mean	Std. Dev.
Unused #1	12.0	0.987
Unused #2	14.1	1.107
Unused #3	13.6	0.575
Exposed	5.1	0.626

Note that for the unexposed samples, eight bars were tested for each sample, whereas only six bars per sample were tested for the exposed sample. The resulting decrease in strength for the exposed samples is more than 61 percent.

The EDX scans, likewise, were performed on exposed and unexposed samples. The results are shown in Table 8.

As can be seen, there was a substantial increase in calcium content in the exposed sample. These calcium concentrations are quite large and may, because of reactions with silica, be a cause for the strength degradation. High alkali levels over longer periods of time may cause chemical reactions to occur between the aluminum-silicon carbide binder and the potassium. This in turn could change the coefficient of thermal expansion and the thermal conductivity of the

Figure 33. Four-Point Bend Testing

Table 8. EDX Test Data for Candle Specimens

Element	Weight Percent				
	Unexposed Specimens			Exposed Specimens	
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2
Ca	0.21	0.228	0.310	42.27	53.48
Al	9.98	10.05	10.07	2.53	1.68
Na	1.06	0.955	1.285	---	---
K	1.91	1.93	1.989	---	---
Si	85.17	85.34	84.68	12.72	1.75

material. The change in thermal properties could cause cracking from thermal stresses due to pulse cleaning.

The SEM photographs taken of the exposed samples are shown in Figures 34 and 35. Photo #1 was taken at 750 magnification and corresponds to the EDX scan #1. As can be seen, some fusion of grains is evident from the photo. The second photo was taken at 3000 magnification, shows areas of what appears to be alkali fusion on the surface. Because the EDX analysis indicates a high level of calcium, this material is probably calcium sulfate (CaSO_4).

The 3000 power SEM photo shows evidence of microcracking. The photo shows a silicon carbide grain with cracks running through the grain. This microcracking significantly affects the material strength.

The XRD analysis revealed the following phases of silicon carbide were present: SiC: 22-1317; SiC 12H (moissonite - 6H): 29-1131; SiC 29-1128; alpha-SiC 22-1273; (SiC) 8F: 29-1129; (SiC) 33R: 22-1316; Beta-SiC: 1-1119. The plots for the three unexposed samples are shown in Figures 36 to 38 and the plot for the exposed sample is shown in Figure 39. There were no major differences in the XRD scans.

As a result of the Acurex analysis, it was concluded that the holes in the candle wall for this particular failed candle were the cause of failure. At this point, it is not known whether the holes occurred during testing or whether they were inherent defects. There were significant changes in strength due to exposure. The candle strength decreased approximately 60 percent from the as-received condition, most probable due to microcracking of the candle structure. The cause of the microcracking is not known at this time. In addition, since the parts of the candle that were examined came from the parts that had fallen to the bottom of the vessel, impact might have caused or contributed to the cracking.

Figure 34. SEM Photograph of Exposed Candle

Figure 35. SEM Photograph of Exposed Candle

3 Figure 36. X-Ray Diffraction Pattern for New Schumacher Candle - Sample 1

Figure 37. X-Ray Diffraction Pattern for New Schumacher Candle - Sample 2

Figure 38. X-Ray Diffraction Pattern for New Schumacher Candle - Sample 3

Figure 39. X-Ray Diffraction Pattern for Used Schumacher Candle

Vibrational phenomenon was a cause listed on the fault tree. Vibration data were collected for an unexposed and an exposed candle. In addition, a high speed dynamic pressure Kistler pressure transducer was mounted in the filter vessel and test data were collected to determine what frequencies were being generated by the combustor.

Two candles were taken to Solar's vibration facility located at Sky Park in Kearny Mesa. One of the candles was exposed during the extended test, but was still intact. The other candle was an unexposed, virgin Schumacher dia-Schumalith. Frequency response curves were obtained for each candle.

The frequency response curves were obtained by placing the candle on two foam blocks to simulate a free-free system. An accelerometer was mounted on the flange of the virgin candle and on the Hastelloy-X cup for the exposed candle. An impedance hammer was used to strike the candle in a fixed location five times. A microprocessor averaged the data. Each candle was struck with the hammer in locations that included both ends, and at 15, 30 and 45 inches from the top flange of the candle.

The data are summarized in Figure 40 for the unexposed or virgin candle, and in Figure 41 for the exposed candle. The virgin candles show much stronger responses whereas the exposed candle has been damped somewhat, perhaps by the presence of dust in the interstices of the candle. The most active frequencies for the virgin candle are in the 200-400 Hz region. The lowest frequency at approximately 7 Hz, responded at about 1.5 times the excitation; the most active response was at 414 Hz and at the flange end of the candle where 32.2 times the excitation was observed. These data are also displayed in Table 9 for both unexposed and exposed candles.

Figure 40. Frequency Response Curves for Virgin Candle

Figure 41. Frequency Response Curves for Exposed Candle

Table 9. Resonant Frequency Data for Virgin and Exposed Candles

Distance from Top Flange, In	Unexposed Candle		Exposed Candle	
	Frequency, Hz	Response, EU/EU	Frequency, Hz	Frequency, Hz
0	7.5	1.48	5.25	1.60
	75	7.98	7.5	0.32
	77.5	14.0	67.75	4.75
	206.25	11.6	69.00	1.86
	213.75	21.7		
	401.25	15.8		
	413.75	32.2		
15	7.5	0.84	5.25	1.12
	77.5	1.57	67.75	4.21
	206.24	1.32	69.0	2.01
	213.75			
	400.0			
	413.75			
30	7.5	0.45	5.5	0.22
	75	7.39	7.25	0.33
	77.5	8.05	67.75	7.38
	207.5	0.32	69.0	3.58
	215.0	0.31		
	401.25	19.3		
	413.75	23.5		
45	6.25	0.37		
	75.0	1.48		
	78.75	1.53	69.0	0.41
	206.25	10.9		
	213.75	13.1		
	401.25	16.1		
	413.75			
60	6.25	0.86	5.26	1.49
	75.0	11.2	5.4	0.95
	78.75	11.8	6.8	0.63
	206.25	17.6	7.0	0.42
	213.75	19.1	67.75	10.7
	400.0	21.8	69.0	5.57
	41.375	25.5		

A test was conducted at the IBSTF with diesel fuel #2 to determine frequency response characteristics of the system. A fast-response Kistler pressure transducer was installed in the filter vessel using one of the window ports. The transducer housing was cooled; this permits measurements to be taken at fairly high temperatures. The signal from the piezoelectric transducer was amplified using a charge amplifier. The amplified signal was then input to a Spectral Dynamics spectrum analyzer. All noise was basically low frequency and below about 100 Hz. In general, the pressure fluctuations were about ± 0.1 psid. A graph of a typical trace is shown in Figure 42. While the pressure fluctuations were negligible in general, fluctuations as high as ± 1 psi were observed, coincident with an airplane taking off. The only significant datum from this test were the increased pressure fluctuations that were observed when planes were taking off. For this reason, a secondary experiment is currently under investigation to observe, solely, the effect of airport-generated noise on the strength of rigidly and non-rigidly mounted candles.

Another experiment was conducted with an accelerometer mounted on a candle in the Hot End Simulation Rig and with a microphone installed in the filter vessel. The experiment was, by necessity, conducted at atmospheric pressure and ambient temperature. However, at a face velocity of 6 ft/min, there was considerable low frequency noise, particularly below 20 Hz. A level of 104 dB was measured at about 10 Hz. There was not much occurring above 20 Hz, with the exception of some noise about 40 Hz. It was pretty much lower intensity white noise above that with no pronounced specific frequencies. The candle manifested responses around 55 Hz, and two peaks near 120 Hz; one was about 115 Hz, the other about 124 Hz. The magnitudes of the responses were 1×10^{-3} for 55 Hz and 1×10^{-4} at 115 Hz and 124 Hz. From this test, it did not appear that system noise was causing the candles to resonate to any appreciable extent.

The effect of the cooled tubesheet was of some concern. In the design phase of the barrier filter system, an ANSYS heat transfer analysis was performed to determine the types of temperature gradients the candle might experience. Effectively, the axial temperature gradients were discovered to occur over the first couple inches of the candle and were not at the point of failure. The location of the failures occurred at a point where the candle was already close to the gas stream temperature.

Extended Candle Tests

As the overall goal is to determine technical feasibility of using candle filters for a direct coal-fired gas turbine system. In order to attain this, it is necessary to first prove the system is viable for a relatively short period of about 50 hrs. Longer tests will eventually be necessary. Following the extended test of May 1990, a number of modifications have been made. First of all, in order to run the IBSTF within the County of San Diego, particulate emissions have to be kept below 0.1 grains/SCF (corrected to 12% CO₂), using a modified EPA method 5, which is even more stringent than EPA Method 5.

In order to meet these requirements, a venturi scrubber system was designed, constructed and commissioned. Tests have been erratic, and an operating permit has not yet been granted. Several tests have been conducted with both coal and diesel fuel #2, and the standard was met

Figure 42. Typical Trace

with diesel with dolomite injected, but has not yet been met with CWS. Modifications have been made to the system to improve performance. These include:

- Adding a filter system downstream of a hydrocyclone circuit to remove micron and submicron size fines from the recycle water stream.
- Adding a strainer in the tubing that goes up to the venturi throat spray nozzles. This was added to remove particulate from the water injection spray so that it is not introduced again into the system.
- Replacing a pump that was used to boost pressure upstream of the hydrocyclones. The replacement pump is a centrifugal pump.
- Replacing the spray nozzles with a variety that is less likely to plug.

Lean PRIS Evaluation

The economic and technical feasibility of using candle filters is by no means assured. For this reason, alternate technologies are being considered. Recently, because of the success of the high temperature PRIS, a lean PRIS is being investigated as an alternate to a barrier filter device. Initial investigations have been paper studies only with testing recommendations. The concept included addition of a glass-like material so as to make the ash sticky enough to adhere to the rods of an impact separator. The initial studies have included an analysis of the operating conditions, and factors that affect the selection of additives. Subsequent studies have included concepts to remove deposits. Dr. Arthur Metcalfe of Metcalfe and Associates, Inc., has been employed as a consultant for this work.

An initial analysis of the operating conditions showed that 2.5 times more material needs to be captured if dolomite is used rather than hydrated lime. This would indicate that if all things are equal, hydrated lime would be preferable. There are unresolved feeding problems with hydrated lime, however, and the particulate size distribution of hydrated lime is finer than dolomite, requiring removal of smaller particulate even though the total amount to be removed is less.

The sorbent selected can be a critical parameter. First of all, the quantity of particulate will vary by a factor of five based on experimental data. This data is shown in Table 10. Approximately 21 pounds of dolomite are required for 100 lbs of coal whereas with hydrated lime, only 4.1 lbs are required. The extra mass attendant to using dolomite has some disadvantages. For instance, an additional 2500 Btu/100-lb dry coal is required to bring the added mass to 1900°F. The heat of dissociation of the extra weight of carbonate, the work to drive the extra reactant into the pressurized system reduces the 4 cent advantage of dolomite to a negligible amount. There is an added cost to dispose of additional material. Furthermore, a 99.6% collection efficiency is required when using dolomite to give an identical downstream concentration to a hydrated lime case with 99.0% collection efficiency.

Apparently, the nature of the particulates is less tractable to treatment by additives when dolomite is used. A review of Phase Diagrams for Ceramists shows no desirable additives that reduce the melting point of MgO from 5070°F to below 1900°F. The large excess of dolomite that is added, as conversions are lower, ensures more unreacted CaO will be present; The high melting point

**Table 10. Addition of Sorbents Per 100 lbs of Coal to
Desulfurize to 75 ppmw SO₂**

Sorbent	% Ca-species	%Ca	Ratio Ca/S Required	Weight/100 lbs Coal Required
Dolomite	57.2% CaCO ₃	22.9	3.4	20.8
PHDL	66% Ca(OH) ₂	29.7	2.4	11.3
HL	95% Ca(OH) ₂	51.4	1.5	4.1

of CaO (~4600°F) and the lack of strong melting point depressants for CaO is an additional factor against the use of dolomite.

A summary of reactants and products from using dolomite and hydrated lime appears in Table 11. The three principal products are unused CaO, unused MgO and CaSO₄. The highest melting material is MgO (5070°F) and it appears only in dolomite. Calcium oxide melts at 4600°F whereas calcium sulfate melts at 2640°F.

Six approaches to improve lean PRIS capture at 1900°F were proposed. These approaches are the melt or fluid approach, the sticky particle approach, the co-deposition approach, the plastic particle approach, the sticky impactor approach, and the molten impactor approach.

In the melt or fluid approach, the lean PRIS would act in the same way as the rich PRIS form which the slag flow in a molten stream. In the sticky particle approach, material is added in sufficient quantity to react with each of the particles to make it "sticky". Each major group of particles would require a different reactant to make it sticky, unless complete reaction and homogenization occurs. Therefore, it is more likely that the additive will provide the same coating on each type of particle. In the co-deposition approach, an inherently sticky substance is added that would be co-deposited on the impact surface. No particle-to-particle reaction or coating within the gas stream would be necessary but once the co-deposit has been made, reaction could occur at that time. In the plastic particle approach, each particle is made plastic so that capture can be achieved by plastic flow at impact in the lean PRIS. This concept may or may not need additives. In the sticky impactor approach, an additive is used to coat the rods in the PRIS to achieve adherence. In the molten impactor approach, the impact surface is in actual fact, a viscous melt to ensure sticking.

In the melt or fluid approach, it is necessary to consider the type of sorbent used, since the viscosity of it differs considerably. The basic approach to modify ash viscosities are to consult the well-known Reid-Cohen correlations. These correlations show ash viscosities as a function of silica ratio, hence composition, and temperature. Thus, one could theoretically adjust the species that affect silica ratio (SiO₂, Fe₂O₃, CaO, and MgO) and obtain a specified viscosity at a given temperature. The silica ratio of slag from the rich PRIS is about 0.53. At 2700°F, such a slag would have a viscosity of 10 poise. This is consistent with the behavior of the rich PRIS. The silica ratio of hydrated lime with entrained slag (slag not captured by the lean PRIS) is estimated to be 0.19, which is much too low to form a glass. The addition of 0.48 lbs of silica to

Table 11. Reactants and Products from Dolomite and Hydrated Lime (per 100 lbs dry coal)

HYDRATED LIME			
Reactants		Products	
Hydrated lime	4.1 lbs	CaSO ₄	5.95 lbs
Sulfur	1.4 lbs	Residual HL	0.64 lbs
Oxygen	2.1 lbs	(less water)	
Total	7.6 lbs	Net Products	6.6 lbs
Loss (water)	1.0 lbs		
Net Reactants	6.6 lbs		
DOLOMITE			
Reactants		Products	
Dolomite	20.8 lbs	CaSO ₄	5.95 lbs
Sulfur	1.4 lbs	Unused CaO	4.21 lbs
Oxygen	2.1 lbs	MgO	4.22 lbs
Total	24.3 lbs	Net Products	14.38 lbs
Loss (CO ₂)	9.87 lbs		
Net Reactants	14.43 lbs		

0.88 lbs of unreacted hydrated lime and 0.65 lbs of slag, would raise the silica ratio to 0.4; this is safely within the glass forming range. To raise the silica ratio to 0.4 for dolomite sorbent, would require addition of 5.75 lbs of silica to give 15.1 lbs of modified slag. The viscosity would be 50 poise at 1900°F, if all the constituents are melted and homogenized.

Several technical problems would need to be addressed with this approach. They include:

- Can reaction between added silica, unused sorbent, and entrained slag be completed in the 200 msec dwell time to give the homogeneous melt that is required to obtain the minimum viscosity?

- If such a melt can be formed, will it be capable of carrying 5.63 lbs of CaSO_4 in 2.01 lbs of melt (hydrated lime) or in 15.1 lbs of melt (dolomite)?

One possibility that might be considered is to remove some of the calcium sulfate by an impact separation step prior to making the silica addition to promote melt formation. This would only be possible with hydrated lime because the nature of the cake on the candle filters when dolomite is used indicates this would probably not be adherent in an impact separator.

A "sticky" particle would be expected to have a viscosity of less than $10^{7.8}$ poise. A removal method other than gravity flow used in the rich PRIS would need to be devised. Reaction between the additive, unused sorbent, entrained slag, and possibly with the calcium sulfate, will require to be uniform to generate particles with uniform compositions and similar degrees of stickiness. This is quite remote. A second possibility is to "coat" the particles and to assume that any subsequent reaction between the particle and its coating would be small in the maximum available time of 200 msec.

In the co-deposition approach, an additive is chosen that is itself sticky. Thus, it does not require reaction with other species. This is similar in nature to the "sticky impactor" approach and is discussed more fully in conjunction with that approach.

In the plastic particle approach, many of the particulates to be trapped are ionic solids, such as CaO , MgO , and CaSO_4 . Ionic crystals become plastic at a temperature above $0.5T_m$ where T_m is the melting point in absolute temperature units. T_m values for a few selected compounds are shown in Table 12. These are the temperatures for the onset of ductility. Two oxides, CaO and MgO are likely to behave as brittle, elastic solids at 1900°F whereas CaSO_4 may be somewhat plastic. Calcium sulfate behaves plastically in the 1000 - 1500°F range.

If the melting points of MgO and CaO were reduced below 4000°F ($0.5T_m = 1770^\circ\text{F}$) by reaction with additives, then plastic behavior of these new solids might be sufficiently plastic to adhere to the impact surface in the lean PRIS. However, the problem becomes one of ensuring enough reaction with all of the particles to form the new solids.

Table 12. Melting Points and Values of $0.5 T_m$ for Selected Ionic Solids

Composition	Melting Point, $^\circ\text{F}$	$0.5 T_m$ $^\circ\text{F}$
MgO	5070	2305
CaO	4600	2071
CaSO_4	2640	1091
NaCl	1474	507

In the sticky impactor approach, impact surfaces would be maintained in a sticky condition by application of a low melting point/low viscosity fluid. The composition could be one of those given in Table 13. The rate of application required can be estimated by assuming that the particles are all of equal size, spherical, and form a close-packed array. In this situation, the interstices constitute 35% by volume of the particles. For a first simplified calculation, we can assume the densities of the two particles are equal and then the deposit on the impact surface for the two sorbents will be as follows:

Table 13. Quantities of Materials for Sticky Impactor

Sorbent	
Dolomite	Hydrated Lime
5.36 lbs CaSO_4	5.36 lbs CaSO_4
4.45 lbs unused CaO	0.88 lbs unreacted CaO
4.22 lbs MgO	0.65 lbs entrained slag
0.65 lbs entrained slag	2.41 lbs sticky binder
5.14 lbs sticky binder	
19.82 lbs total	9.30 lbs total

If calcium sulfate is assumed self-sticking, then the sticky binder will be needed for the entrained slag and unreacted calcium oxide. This lowers the required sticky binder to 3.26 lbs for the dolomite case and to 0.54 lbs for the hydrated lime case. The method of application of the "sticky" binder might be via the co-deposition approach or by some other application method.

In the molten impactor concept, particles would impact on a molten surface that would transport the particles away by flow with possible purification and recycle of the molten material. The molten surface would need to have adequate viscosity to withstand the aerodynamic drag. The most likely candidate for the molten material is a viscous silica-based glass. Potential problems might include the necessity for constant additions of silica to keep the silica ratio at the desired level.

Also, the working range at 1900°F of silica glasses is small. Additions of viscosity-reducing glass formers such as B_2O_3 and CaF_2 would be essential. Also, the lean PRIS would require considerable monitoring to control the melt as the composition of the slurry changes, and as the load on the turbine varies.

5. PHASE II - TASK 4 - COAL FUEL SPECIFICATION DEVELOPMENT

5.1 SPECIFIC ITEMS OF PROGRESS

- Coal slurries tested in the combustor rigs were varied with wide ranges of fuel specifications:
 - Coal loadings in slurries have been extended from 43.4 to 60.6 wt%, and ash contents from 2.3 to 12.8 wt%.
 - Varieties of coal sources with low volatile matter (25.8% in Upper Freeport coal) to high volatile matter (39.4% in Utah's Soldier Creek coal) have been tested.
 - Coal particle sizes in the slurries have ranged from 25 to 100 μm with the mean size between 7.3 to 21 μm .
 - Ash fluid fusion temperatures (under reducing conditions) were extended to a wider range between 2300 to 2700°F.
- Twelve combustion testing fuels have been prepared and tested completely in the subscale combustor.
 - The test fuels were prepared with varieties of fuel specifications such as coal rank/reactivity, coal loading, ash content, particle size, and ash fusion temperature.
 - The combustion results showed that TSSC was capable of utilizing wide ranges of coal specifications without deteriorating the combustion performance.
- The slag samples collected from the primary-zone were diluted and contaminated by the refractory.
- The slag samples collected from the PRIS showed less enrichment with refractory alumina, but retained a significant amount of sodium.
- The slag droplets collected from the water-quenched slag pit were brittle, shining, black spherical glassy materials with fused surface.
- Analyses of the candle dust indicated spent sorbent acting as a capture for coal alkali.
- Laboratory analyses showed that iron present in the slag was responsible for the attack at the worn PRIS silicon carbide rods.

- The leachable metal toxicity tests for studying the slag and candle dust disposal showed the extract metal concentrations well below the published EPA regulatory levels.
- Analyses of a water sample from the water-quenched slag pit showed no significant elements leached during the slag quench operation.
- Slurry was prepared on-site by the leasing of a unit from a Drais grinding mill and slurring system.
- The properties of slurry prepared on-site by Drais Mill were largely dependent on the grinding media, feed rate, coal particle size and hardness, coal loading, and dispersant used.
- Initial and finish grinding tests were completed and the results were utilized for the design and operating criteria of slurry fuel preparation and for the fuel cost projection.
- The first bulk lot (4500 gallons) of slurry prepared by AMAX R&D has been shipped to Peoria for the full-scale combustion testing:
 - The specified properties of bulk-lot slurry were based on the design goals and the operating experience from combustor rig testing.
 - The properties of bulk-lot slurry were checked and ensured after seven weeks of storage before the first full-scale combustor testing.
 - Precautions of slurry handling and slurry waste treatment were taken and a handling procedure was prepared for the full-scale fuel system.
 - A new agitator system was evaluated for installing in the fuel storage tank.
- Fuel costs were updated and projected in a spreadsheet on various scenarios to supply fuels for a coal-fueled Centaur Type H gas turbine cogeneration system.

5.2 DISCUSSION

5.2.1 Coal Fuel Specifications

Fuel Specification

Coal slurries tested in the subscale combustor rigs were varied with wide ranges of fuel specifications. Table 14 updates the ranges of CWM properties and compositions tested so far at Solar's TSSC. The majority of slurry fuels were formulated from eastern Kentucky coals, except that a Pittsburgh-seam Powhatan coal that has been used in the sorbent injection testing. Recently, in the combustor performance runs slurries made from the Upper Freeport coal (in Pennsylvania), Illinois #6 coal, and Utah's Soldier Creek coal have also been tested. The Upper

Table 14. Ranges of CWM Fuel Properties Tested at Solar

Slurry Loading	43.4-60.6 wt%
Ash Content (Coal Basis)	2.3-12.8 wt%
Particle Size	
Top Size	25-100 μm
Mean Size	7.3-21 μm
Slurry Viscosity (100 sec^{-1})	150-470 cp
Slurry Heating Value (LHV)	5452-7801 Btu/lb
Volatile Matter (Coal Basis)	25.8-39.4 wt%
Sulfur Content (Coal Basis)	0.43-3.26 wt%
Nitrogen Content (Coal Basis)	1.02-2.19 wt%
Alkali Content (Coal Ash Basis)	
Na_2O	0.3-2.6 wt%
K_2O	0.3-2.7 wt%
Ash Fluid Fusion Temperature	
Reducing	2300-2700+°F
Oxidizing	2500-2700+°F

Freeport coal contains a relatively low volatile matter (25.8 wt%) compared to the baseline fuel (~35%), while the Soldier Creek coal has a high volatile (39.4%). TSSC combusted the slurry formulated from the low-volatile coal satisfactorily without any difficulty. Accepting a lower volatile content could widen the selection of coal source. Certain attractive coals with low sulfur in the West Virginia/Kentucky areas have below 30% of volatile matter.

Slurries with the coal loading from 43.4 to 60.6 wt% and the ash content from 2.3 to 12.8 wt% have been tested in Solar's combustor rigs. It appears again that Solar's two-stage slagging combustor design can tolerate wide ranges of coal loading and ash content without noticeable impact on combustor performance. A higher coal ash did result in faster refractory degradation and in increasing the slag coating and accumulation on the combustor wall. The combustor test results also showed the TSSC was capable of utilizing wide ranges of coal particle size and had little ill effects on the combustor performance. The coal particle sizes in the slurries have been ranged from 25 to 100 μm with the mean size between 7.3 to 21 μm .

The slurry viscosity was maintained around 200-300 cp @ 100 sec^{-1} with emphasis on lowering the amount of stabilizer used. The sulfur in coal varied from 0.43 to 3.26%. Illinois #6 coal with sulfur content at 2.61% (on ash-free dry coal basis) has been used in one of the combustor performance fuel. The alkali content (on coal ash basis) was ranged from 0.3 to 2.6% of Na_2O and 0.3 to 2.7% of K_2O , respectively. This is corresponding to about 82 to 978 ppm of total alkali

content in the slurry feed. Ash fluid fusion temperature has been extended to a wider range between 2300 to 2700°F (under reducing conditions) in the most satisfied operation when a water quench bath used for the slag capture.

Based on the design goals and the operating experience from the combustor rig testing, the first bulk lot (4500 gallons) of slurry fuel has been prepared at AMAX R&D and shipped to Peoria for the full-scale combustor testing. Table 15 summarizes the important slurry properties present in the full-scale testing fuel. The slurry was formulated by blending Kentucky 4A and Elkhorn coals with approximately 54 wt% loading and 2.9% ash content. The top particle size in slurry was 98.7% passing 45 μm and 99.9% passing 75 μm with the mean size of 11.9 μm . The slurry viscosities were around 210 cp @ 100 sec^{-1} and 305 cp @ 1000 sec^{-1} . The slurry coal contains 0.76% sulfur (on ash-free dry coal basis) and 0.63% Na_2O and 1.08% K_2O (on coal ash basis), respectively. Ash fluid fusion temperature (under reducing conditions) was adjusted with a small amount of Hematite additive to remain below 2500°F. Flocon stabilizer (0.1% on coal basis) and A-23 dispersant (1% on coal basis) were also added to ensure the stability of slurry for the large quantity and long period storage.

Table 15. Slurry Properties for Full-Scale Combustor Testing

Batch	W
Coal Source	Kentucky 4A/Elkhorn
Slurry Loading	54.1 wt%
Ash Content	2.94% (Slurry Basis)
Particle Size	
Top Size	45 μm (98.7% passing)
Mean Size	11.9 μm
Slurry Viscosity	
@ 100 sec^{-1}	210 cp
@ 1000 sec^{-1}	305 cp
Slurry LHV	7064 Btu/lb
Volatile Matter	34.33% (Coal basis)
Sulfur Content	0.75% (Coal basis)
Nitrogen Content	1.48% (Coal basis)
Alkali Content:	
Na_2O	0.63% (Coal Ash basis)
K_2O	1.08% (Coal Ash basis)
Ash Fluid Fusion Temperature	
Reducing	2497°F
Oxidizing	2655°F

A summary of CWM fuel properties tested at Solar's combustor rigs (TSSC, IBSTF and HESR) and full-scale combustor is listed in Appendix A.

Combustion Testing Fuels

Twelve combustion testing fuels have been prepared and tested in the subscale combustor. Table 16 compares and summarizes the fuel properties, composition, and coal sources. The baseline fuels (S-1 and S-2) were prepared from the blend of Kentucky 4A/Elkhorn coals with or without the addition of stabilizer. S-3, S-4 and S-5 were prepared with different coal loading. S-3 and S-5 have blended coarsely and finely ground slurries to achieve the "bimodal" effect for obtaining a high solids loading. S-3 was formulated at 58.2% coal and S-4 at 50% loading, while S-5 prepared without dispersant and stabilizer only could reach 43.4% coal loading.

S-6 and S-7 were prepared with higher ash contents where S-6 slurry contained 4.80% ash (or 8.84% ash on dry coal basis) and S-7 contained 6.96% ash (or 12.81% on dry coal basis). These two coal ash contents are about double or triple amounts of baseline fuel. S-8 had a particle top size of 25 μm and mean size of 7.3 μm and S-9 had 50 μm and 15.4 μm , respectively.

The last three slurry fuels, S-10, 11, and 12 were prepared from different ranks and reactivities of coals including a medium volatile Upper Freeport, a western Utah bituminous, and a midwestern Illinois No.6, respectively. Upper Freeport's medium volatile coal contains about 26% volatile matter compared to about 35% in eastern Kentucky coals. One of our early studies on coal source selection indicated that bituminous coal from Utah appears to have the best potential for consumption in the California market. And, Illinois Basin coals represent the most economic coal sources for the midwestern coal-fired gas turbine markets.

As shown, the above test fuels were prepared with varieties of fuel specifications such as coal rank/reactivity, coal loading, ash content, particle size, and ash fusion temperature. The combustion results indicated that Solar's two-stage slagging combustor could tolerate these differences of fuel properties without deteriorating the performance.

Slag Composition and Characterization

The chemical and physical composition and properties of ash slag are critical to successful direct combustion of coal as it reflected the very nature of the slagging combustor. All slag properties - fusion temperature, viscosity, surface tension, thermal properties - will relate back to the ash composition of parent coal and the thermal history during the slag formation.

The appearance of slag samples from the combustor depends on the location where the slag collected. The slag droplets collected in the water quenched slag pit are nearly black, glassy materials with fused surface. These droplets are brittle, shining spherical particles with a diameter about 5-7mm. Some of these droplets can be crushed by finger pressure without difficulty.

Water-quenched slags collected from the combustor performance fuel tests (S-1 to S-12) were examined for their composition and slag fusion characterization. The slag composition and ash fusion properties are reported in Table 17. In general, the slag samples were high in alumina compared to their parent coal ashes. The slag samples also appear gaining some Fe_2O_3 and

Table 16. Properties and Compositions of Combustion Testing Fuels

CWRI	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12
TSSC Test No.	48	44	49	50	53	51	52	54	55	56	57	58
----- Kentucky 4A/Ethom -----												
Coal Source										Upper Freeport	Soldier Creek	Minda No. 6
Moisture Content (wt%)	45.58	45.27	41.34	49.81	56.56	45.71	45.85	45.48	45.77	46.22	45.88	45.89
Coal Content (wt%)	53.88	54.20	52.17	49.95	43.44	53.60	53.60	53.77	53.75	53.05	53.74	53.50
Ash Content (wt%)	2.05	2.08	2.33	2.03	1.72	4.80	6.98	2.10	2.13	5.86	2.78	3.47
A-21 (wt% of coal)	0.875	0.945	1.525	0.89	0.00	1.27	1.30	1.35	0.89	1.37	1.10	1.10
Rocon (wt% of coal)	0.04	None	0.016	0.016	0.00	0.005	0.02	0.02	0.01	None	0.01	0.005
Particle Size												
% Passing 100 micron	100.00	100.00	99.99	99.94	99.41	99.99	100.00	99.99	99.90	-	99.99	99.94
% Passing 75 micron	99.88	99.88	99.87	99.89	98.67	99.85	99.85	99.95	99.43	99.85	99.87	99.59
% Passing 45 micron	98.75	98.78	97.38	98.32	94.87	98.91	98.88	99.84	98.58	99.28	99.08	98.71
% Passing 37 micron	97.84	97.84	96.85	97.78	93.48	98.22	98.42	99.44	94.28	98.66	98.50	96.11
% Passing 30 micron	93.84	93.84	91.09	94.21	87.84	94.09	96.40	99.22	90.35	96.42	94.78	95.31
% Passing 20 micron	85.35	85.35	82.18	87.94	78.89	90.81	91.28	93.15	71.83	90.83	85.88	81.28
% Passing 15 micron	75.81	75.81	69.30	73.18	65.77	83.20	81.63	89.48	68.87	87.01	74.69	63.84
% Passing 10 micron	68.51	68.51	62.50	66.13	48.29	68.75	64.48	74.87	41.57	73.44	58.03	48.80
% Passing 8 micron	61.04	61.04	45.49	47.44	39.93	55.98	55.53	67.81	34.29	65.01	48.23	38.41
% Passing 6 micron	43.32	43.32	39.45	39.80	31.17	48.48	48.25	58.39	28.11	54.58	39.58	30.97
% Passing 4 micron	33.73	33.73	29.01	25.78	20.93	35.47	34.78	41.94	19.40	40.85	28.86	23.08
% Passing 3 micron	27.04	27.04	21.73	18.78	14.73	27.57	27.57	32.25	14.52	31.34	22.39	17.98
% Passing 2 micron	19.71	19.71	15.01	11.94	8.34	13.35	18.87	21.30	9.16	19.85	14.96	11.29
% Passing 1 micron	9.52	9.52	5.44	3.66	1.84	6.23	5.54	6.55	3.37	6.83	4.98	3.15
Mean Size (micron)	10.8	10.8	12.7	11.4	15.4	9.4	9.3	7.3	15.4	8.3	11.0	12.9
Slurry Viscosity (cp)												
@ 100/sec	300	310	300	300	375	225	220	240	250	250	275	280
@ 1000/sec	280	280	600	185	110	270	300	330	280	115	310	390
Slurry LHV (Btu/lb)	7148	7162	7712	6481	6452	6857	6267	7092	7049	6702	6729	6585
Coal Characteristics												
Proximate Analysis (wt%)												
Ash	3.77	3.77	3.96	4.03	3.98	8.94	12.81	3.85	3.93	10.89	5.14	6.48
Volatiles	35.29	35.29	35.53	35.18	35.21	35.80	32.99	35.04	35.73	25.78	39.36	38.27
Fixed Carbon	60.94	60.94	60.49	60.78	60.83	55.36	54.20	61.11	60.34	63.33	55.50	55.25
Ultimate Analysis (wt%)												
Carbon	80.85	80.85	80.47	80.48	81.17	78.40	72.51	80.48	80.58	87.53	80.81	80.21
Oxygen	11.50	11.51	11.58	11.83	11.09	15.85	20.31	11.77	11.88	4.34	11.79	10.08
Hydrogen	6.31	6.31	6.34	6.33	5.46	5.14	4.58	5.18	5.37	5.18	5.41	5.59
Nitrogen	1.77	1.77	1.77	1.52	1.57	1.59	1.52	1.73	1.52	1.49	1.32	1.53
Sulfur	0.57	0.57	0.86	0.84	0.71	1.02	1.08	0.84	0.87	1.45	0.87	2.81
Ash Composition (wt%)												
SiO ₂	46.58	46.58	48.31	47.10	48.83	53.59	56.74	48.85	47.47	37.70	51.12	48.88
Al ₂ O ₃	28.24	28.24	30.24	28.89	28.49	22.92	21.32	26.74	28.31	24.59	18.30	22.96
Fe ₂ O ₃	12.12	12.12	10.56	12.09	10.69	14.44	13.84	11.45	10.70	11.92	7.87	20.08
CaO	3.99	3.99	3.92	4.88	3.88	2.78	2.12	4.29	4.06	6.13	8.72	1.89
MgO	1.29	1.29	0.50	0.71	0.54	0.63	0.56	1.10	1.84	0.95	1.86	0.38
Na ₂ O	1.01	1.01	1.10	1.25	1.11	0.73	0.58	1.12	1.16	0.26	1.35	0.45
K ₂ O	1.08	1.08	0.92	0.89	0.90	1.40	1.49	0.95	0.82	2.34	0.59	2.72
TiO ₂	0.16	0.16	0.22	0.19	0.20	1.07	1.14	1.07	0.90	1.16	0.59	0.98
P ₂ O ₅	3.11	3.11	3.08	3.59	4.29	0.25	0.17	0.23	0.17	0.01	0.16	0.18
SO ₃						1.60	1.93	3.57	4.41	5.60	8.71	1.17
Ash Fusion Temp. (°F)												
Initial Deformation	2659/2310	2659/2310	2440/2254	2445/2381	2372/2311	NA/2179	NA/2089	2479	2369	2499/2304	2255/2132	2487/2057
Softening	2688/2375	2688/2375	2574/2435	2586/2425	2586/2435	NA/2287	NA/2136	2504	2428	2537/2351	2273/2154	2527/2085
Hemispherical	+2700/2424	+2700/2424	2686/2561	+2700/2502	+2700/2508	NA/2395	NA-2392	2549	2486	2593/2385	2302/2209	2532/2155
Fluid	+2700/2687	+2700/2687	+2700/2672	+2700/2631	+2700/2700	NA/2582	NA/2520	2577	2871	2639/2595	2415/2399	2594/2439

Table 17. Slag Compositions and Properties From Combustion Testing Fuel Runs

	S-1 Slag	S-2 Slag	S-4 Slag	S-5 Slag	S-6 Slag	S-7 Slag	S-8 Slag	S-9 Slag	S-10 Slag	S-11 Slag	S-12 Slag
Pulverized Slag Composition, %											
SiO ₂	27.80	40.81	51.20	31.49	53.06	62.76	39.50	43.80	44.20	50.70	45.3
Al ₂ O ₃	34.37	31.67	30.50	45.00	33.22	23.93	24.80	31.20	30.00	25.80	27.0
TiO ₂	0.74	1.04	0.92	0.79	1.00	1.23	0.93	1.06	1.13	0.84	0.96
Fe ₂ O ₃	9.03	12.54	14.10	8.94	13.51	14.23	11.30	16.50	15.80	10.90	15.6
CaO	10.17	3.55	4.09	3.61	2.68	1.94	4.82	3.94	5.49	7.05	4.35
MgO	5.10	0.56	0.92	0.73	0.73	0.69	1.17	0.91	0.94	1.62	1.15
SiO	0.13	0.21	0.22	0.08	0.13	0.08	0.16	0.22	0.08	0.16	0.09
Na ₂ O	0.85	1.25	1.18	0.637	0.851	0.625	1.08	1.34	0.50	0.83	0.598
K ₂ O	0.56	0.969	0.912	0.823	1.15	1.39	0.936	0.99	2.38	1.03	1.82
P ₂ O ₅	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.02	<0.02	<0.02
MnO ₂	0.04	0.04	0.046	0.04	0.048	0.050	0.04	0.05	0.05	0.05	0.04
Cr ₂ O ₃	-	-	-	0.10	-	-	3.25	-	-	-	-
NiO	-	-	-	0.03	-	-	0.04	-	-	-	-
PbO	<0.02	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.02	<0.02	<0.02
V ₂ O ₅	0.04	0.04	0.037	0.02	0.032	0.30	0.02	0.05	0.05	0.020	0.04
Total Carbon	10.0	0.052	0.056	0.053	0.015	0.023	0.145	1.37	0.021	0.024	<0.01
SO ₃	0.67	<0.01	0.028	0.028	0.038	0.040	0.028	0.058	0.038	0.016	<0.01
Water Soluble Na ₂ O	0.021	0.007	0.002	0.005	0.002	0.002	0.002	0.003	0.001	0.003	0.003
Water Soluble K ₂ O	0.007	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.008
SiO ₂ Al ₂ O ₃	0.81	1.29	1.68	0.70	1.60	2.62	1.59	1.40	1.47	1.97	1.68
Base/Acid Ratio	0.41	0.26	0.26	0.19	0.19	0.19	0.30	0.31	0.33	0.28	0.32
Ash Fusion Temperatures, °F											
Reducing, Initial	2357	2325	2325	2607	2514	2437	2521	2424	2431	2278	2195
Reducing, Softening	2454	2377	2473	2700+	2538	2455	2603	2469	2448	2320	2417
Reducing, Hemispherical	2463	2467	2502	2700+	2575	2477	2647	2476	2463	2336	2445
Reducing, Fluid	2520	2698	2630	2700+	2685	2632	2700+	2700+	2700+	2700+	2700+
Oxidizing, Initial	2494	2589	2493	2700+	2580	2531	2585	2593	2523	2369	2507
Oxidizing, Softening	2496	2639	2610	2700+	2614	2548	2680	2660	2585	2450	2579
Oxidizing, Hemispherical	2506	2700+	2659	2700+	2644	2604	2698	2676	2624	2483	2595
Oxidizing, Fluid	2539	2700+	2700+	2700+	2695	2688	2700+	2700+	2700+	2700+	2700+

alkali Na_2O and K_2O . The analyses of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio showed that the slags were diluted and contaminated by the refractory. Higher fluid temperatures in slag samples (determined by ASTM measurement) further indicated alumina contamination in slags from the refractory. The slag from S-8 fuel contained 3.25% Cr_2O_3 , which could come either from the refractory used in the impactor or from metal worn off the chromium steel balls used during the extra fine grinding operation.

Three slag samples collected after IBSTF No.9 duration test were examined for their composition and fusion properties (Table 18). Among slags, one was obtained from the primary-zone slag pit and the other two samples were taken from PRIS's slag outlet and wall, respectively. As shown in Table 18, the primary-zone slag was high in alumina indicating the contamination of refractory. However, the slag samples from the PRIS area showed lesser enrichment in alumina

Table 18. Properties of Primary-Zone and PRIS Slags

	Primary Zone Slag	PRIS Slag		Ash In Parent Fuel
		Outlet	Wall	
Composition, %				
SiO ₂	33.8	54.0	50.8	53.5
Al ₂ O ₃	47.4	28.6	30.9	21.2
TiO ₂	0.99	1.08	0.96	1.00
Fe ₂ O ₃	10.1	7.16	6.24	10.9
CaO	3.60	3.06	2.54	4.00
MgO	0.48	0.67	0.67	0.05
SrO	0.22	0.39	0.44	
Na ₂ O	1.13	1.83	2.08	2.60
K ₂ O	0.652	1.07	1.10	1.30
P ₂ O ₅	<0.01	<0.01	<0.01	0.20
MnO ₂	0.04	0.06	0.07	
Cr ₂ O ₃	0.08	0.06	0.05	
NiO	0.06	0.06	0.07	
CuO	0.01	0.02	0.02	
PbO	<0.01	<0.01	<0.01	
V ₂ O ₅	0.025	0.034	0.028	
SO ₃	<0.005	<0.005	0.005	
Water Soluble Na ₂ O	0.004	0.005	0.005	
Water Soluble K ₂ O	0.001	0.001	0.001	
SiO ₂ /Al ₂ O ₃	0.71	1.89	1.65	2.52
Base/Acid Ratio	0.197	0.170	0.158	0.249
Ash Fusion Temperatures, °F				
Reducing, Initial	2348	2209	2305	2250
Reducing, Softening	2377	2293	2383	2275
Reducing, Hemispherical	2410	2334	2418	2350
Reducing, Fluid	2485	2517	2601	2610

compared to the coal fuel ash. Significant amounts of sodium were retained in slags, as observed 1.13% is primary-zone slag and 1.83-2.08% is PRIS slags, despite the refractory dilution. In addition, the slag samples have fluid fusion temperatures somewhat lower than its parent coal ash, especially those of primary-zone slag, indicating the slag contains more homogeneous fluid parts of coal ash.

Candle dust collected after IBSTF No, 9 duration test was also analyzed for its composition and particle size distribution. The candle dust sample was collected from the secondary filter vessel after the run which used the dolomite sorbent injection. The sample consists mainly of spent sorbent with small amount of fly ash (coal particulate) escaped from PRIS. The particle sizes of dust were found to be essentially minus 65 mesh (212 μm) compared to 50 mesh (297 μm) of the original dolomite sorbent (D-100) as analyzed in Table 19. The particles median size was

Table 19. Particle Size Distribution of Candle Dust and Dolomite Sorbent

Particle Size (μm)	Cumulative Weight (Passing %)	
	Candle Dust	Dolomite D-100
297	--	99.3
212	98.3	--
150	97.6	86.8
106	95.9	70.0
75	92.9	55.3
54	86.2	35.5
45	85.9	28.4
38	77.5	23.2
30	75.7	19.5
20	58.2	12.2
15	35.3	8.4
10	14.0	4.8
8	7.8	3.3
6	4.3	1.7
4	1.0	1.3
2	0.4	0.9
Median Size (μm)	17.0	72.0

dropped from 72 μm of the original sorbent to 17 μm in the candle dust. The D-100 dolomite has 4.8% passing through 10 μm while the dust sample contains 14.0% finer than 10 μm . The composition analyses of candle dust (along with the dolomite sorbents) are listed in Table 20. As observed, a significant amount of alkali (Na_2O and K_2O) was accumulated in the dust sample. This indicates spent sorbent acting as an alkali capture because the original dolomite sorbents contain only a trace of alkali. The X-ray analysis showed that the dust was primarily anhydrous calcium sulfate (CaSO_4) and a moderate amount of magnesium oxide (MgO).

Table 20. Composition Analyses of Candle Dust and Sorbent

Composition, %	Candle Dust	Dolomite D-303	Dolomite D-100	Hydrated Lime
SiO_2	5.04	0.65		
Al_2O_3	2.82	0.05		
TiO_2	0.11	<0.01		
Fe_2O_3	1.59	0.12		
CaO	31.02	29.80		
MgO	20.06	18.90		
SrO	0.06	<0.01		
Na_2O	0.404	<0.001	<0.001	0.010
K_2O	0.184	<0.001	0.002	0.028
P_2O_5	0.05	0.08		
MnO_2	0.06	0.03		
PbO	<0.01	<0.01		
Cr_2O_3	0.10	<0.01		
NiO	0.07	<0.01		
V_2O_5	0.017	<0.01		
SO_3	44.5	0.004		
CO_2	0.57	47.1		
X-ray Diffraction				
Dolomite	--	Predominant		
Calcite	--	Trace		
Calcium Sulfate	Predominant	--		
Magnesium Oxide	Moderate	--		

A section of the silicon-carbide rod inserted for the PRIS (from IBSTF No. 9 run) was examined to determine any correlation or key elements of slurry fuel which could cause the facts of PRIS rod erosion and deposition. The worn area of PRIS rod was studied for signs of possible attack by the fuel iron and/or alkali vapor present in the hot gas.

The results of laboratory photograph analysis of the PRIS silicon carbide rod showed numerous metallic spheres in the slag and several large metallic globs (0.2-0.4 mm) at the silicon carbon-slag interface. It also showed wherever a metallic glob was observed in contact with the silicon carbide there was an obvious reaction resulting in corrosion of the silicon carbide. The various phases present in the cross section were analyzed in a scanning electron microscopy using energy dispersive spectroscopy (EDS). It was found that the metallic particles consisted of roughly 70% iron and 30% silicon. No foreign elements like sodium were present in the SiC tube within detection limits.

Silicon carbide is highly resistant to most substances at high temperature but is readily attacked and dissolved by liquid ferrous metals. The iron present in the slag was therefore responsible for the attack of PRIS rods. Controlling iron content in slurry fuels or replacing the PRIS-rod silicon carbide by another material, such as alumina, aluminum nitride, or boron nitride, is recommended.

Slag/Ash Waste Disposal

The EPA Toxicity Characteristic Leaching Procedure (TCLP) was applied to a minus 35 mesh split of a slag sample to determine the leachable metal toxicity for slag disposal. The slag sample was obtained from the primary zone after burning S-1 slurry in Run #48 of TSSC testing. The applied TCLP is the latest official method published in the March 29, 1990 Federal Register (Vol. 55, No. 61) by National Safety Council. The test results are shown in Table 21. As observed, the concentration of each of the regulated metals in the slag leaching solution was well less than the allowable level specified by the EPA. In other words, it does not appear that this slag sample would be classified as a hazardous waste. Usually, a waste is classified as a toxicity characteristic waste if chemicals listed are at, or above, the specified regulatory levels. In that case the material will be subject to all RCRA (Resource Conservation and Recovery Act) hazardous waste requirements.

The candle dust was also subjected for EPA leachability study to determine any leachable metal toxicity (Table 21). As shown, the extract concentrations of heavy metals were well below the published EPA regulatory levels, except for mercury. It is believed that the high mercury value was attributed to the mercury background interference from high sulfur and/or calcium in the spent sorbent. The above results of EPA testing will help to design disposal strategies for the combustor waste products.

A water sample taken from the water-quenched slag pit and a sample of the source water were determined to find which elements leached from the slag during quenching. The concentrations of elements of particular interest which were found in these two water samples are given in Table 22. A concentration of calcium, 79 ppm, was measured in the slag pit water compared to 58 ppm in the original source water; while sulfur was 55 ppm in slag pit versus 53 ppm in the source water. It does not appear that any of the listed elements leached from the slag to any significant extent during the slag quenching operation.

Table 21. Leachability Measurement of Slag and Candle Dust

Constituent	Slag Extract (ppm)	Candle Dust Extract (ppm)	EPA HW No.*	EPA Regulatory Level (ppm)
Aluminum	<0.01	<0.02		
Arsenic	--	<0.02	D004	5.0
Barium	0.4	0.11	D005	100.0
Beryllium	--	<0.05		
Boron	--	0.14		
Calcium	--	>2800		
Cadmium	<0.005	0.006	D006	1.0
Chromium	0.006	0.32	D007	5.0
Cobalt	--	<0.01		
Copper	<0.005	<0.005		
Iron	--	<0.005		
Lead	<0.05	0.08	D008	5.0
Magnesium	--	960		
Manganese	--	<0.001		
Mercury	<0.01	<0.5	D009	0.2
Molybdenum	--	0.56		
Nickel	<0.01	<0.01		
Selenium	<0.01	<0.01	D010	1.0
Silver	<0.01	<0.01	D011	5.0
Sulfur	--	900		
Tungsten	--	0.08		
Vanadium	0.07	<0.01		
Zinc	<0.005	0.0085		
*EPA Hazardous waste number.				

Table 22. Slag-Quench Water Analysis

	Symbol	Concentration, ppm	
		Source Water	Slag Pit
Elements			
Arsenic	As	<0.02	<0.02
Barium	Ba	0.07	0.16
Cadmium	Cd	<0.02	<0.02
Calcium	Ca	58	79
Chromium	Cr	<0.01	<0.01
Iron	Fe	0.005	0.005
Lead	Pb	<0.1	<0.1
Mercury	Hg	<0.01	<0.01
Potassium	K	5.4	4.8
Selenium	Se	<0.4	<0.4
Silver	Ag	<0.02	<0.02
Sodium	Na	92	90
Sulfur	S	53	55
Dissolved Solids		531	597
pH		7.05	7.78

5.2.2 Fuel Preparation Tests

Integrated Fuel Preparation System

The lease unit of Drais grinding mill and slurring equipment arrived on site. The Drais Perl Mill is a higher speed version of the stirred ball mill which has been used to grind coal and prepare slurry fuel by AMAX currently and by other coal slurry manufacturers in the past. The purpose of this rental arrangement is to gain the experience for integration of the on-site slurry fuel preparation equipment with the bench scale combustor rigs and with the full scale engine testing facility.

Figure 43 shows the outline drawing of Drais Mill and slurry preparation system. Coal, typically of 1/16 in. x 0 size is pneumatically transported into a hopper by pulling a negative pressure on the hopper and then vacuuming the coal out of the drum container. The coal then is mass flow controlled down the feed hopper. Liquid water and additive (if necessary) are also flow controlled, entering with coal at the mouth of the screw feeder. Coal and carrier liquid are then transported into the mill at a controlled rate set by the desired grinding size. As the coal and water are fed into the bottom of the mill they are commingled with the grinding media and under go high shear and impact grinding as they pass through the mill. The discharge end of the mill is equipped with

Figure 43. Outline of Drals Perl Mill and Slurry Preparation System

a frictional gap separator, which retains the grinding media while allowing the slurry product to flow out of the discharge nozzle. The process variable such as coal feed rate, liquid feed rate, size and amount of grinding media, rotor speed, separator gap can be controlled proportionally or independently of each other to meet the optimum product requirements.

A total of four tests is scheduled using two different mesh size of coal feedstock. One is boiler grade which has particle size 75% below 200 mesh and the other has the top size below 16 mesh. A summary of the Tests and goals of each test are listed in Table 23. The key measurements of slurry outputs will include the product particle size distribution, production rate, and slurry viscosity and stability. The final test will demonstrate to burn the fresh slurry prepared on site at the bench-scale combustor rig.

Table 23. On-Site Grinding and Slurry Preparation

Test Goal	Coal Used
Test 1: Shakedown/Grinding Mill Installation	1 drum
Test 2: Initial Grinding Mill Operation • Measure particle size distribution	1 drum boiler grade coal 1 drum 16 mesh coal
Test 3: Operate Grinding Mill • Measure slurry production rate • Measure slurry stability • Produce batch slurry and test at TSSC	4 drums
Test 4: Produce On-Site Slurry • Test at TSSC on same day	3 drums
	<hr/> Σ 10 drums

The proposed full-size slurry fuel preparation will be processed first via a two-stage coal particle size reduction. The purchased coal will be received in size ranges about 2-inch x 0. It requires a crushing stage to reduce the size to about 16 mesh before feeding into a wet grinding (i.e., Drais Mill) for slurry preparation. Types of crusher are being evaluated so that the suitable capacity equipment could be used in the slurry preparation for the full-scale proof of concept 100-hr engine test. For our application of reducing 2 in. x 0 coal to a 16 mesh product with 5-7% surface moisture at a rate of approximately 2.5 ton/hr, a hammer mill with a 25 HP, 1800 RPM motor, V-belt drive and guard-mounted on a steel subbase was identified. Price quotes for crushing equipment have been requested from Buffalo Hammer Mill (Buffalo, NY) and American Pulverizer Company (St. Louis, MO). Tumbling mills (i.e., rod, ball mills) and other crushing equipment for the coarse size reduction are also being evaluated.

Preliminary analyses indicate that slurry produced by on-site Drais Mill has stable properties without forming any hard park on the bottom of drum after 2 weeks before combustion. The slurry was formulated without adding the stabilizer. The viscosities were measured between 200-450 cp @ 100 sec⁻¹ and 250-400 cp @ 1000 sec⁻¹. The solid loadings of preliminary tests were determined in the ranges of 48.8 to 50.7 wt% when the coal and water ratio was set at 50:50 at

the grinding mill. The particle size distribution of slurry is under measurement by size screening in conjunction with a particle settling velocity analyzer (Sedigraph method) and by a Microtrac laser light-scattering particle size analyzer.

Equipment costs, and probable operating costs, for systems capable of handling 2.0 to 2.5 tons per hour Illinois coal to produce 1000 gallons per hour of slurry for the full-scale engine testing, are estimated as the following:

Grinding Mill

Specifications:

Feeding Rate

9,720 lb/hr

972 gallons/hr

Grinding chamber capacity

66 gallons

Costs with Integrated Grinding Mill and Slurrying Preparation System:

Grinding mill	\$850,000
Crusher/Conveyor	10,000
Support equipment & installation	100,000
Coal cost @ \$25/ton	6,250
Coal transportation cost (@ \$20/ton for Illinois coal)	5,000
Labor (manpower @ \$50/hr)	5,000
Utilities	2,500
	<hr/>
	Σ \$ 978,750
Others (@ 10%)	97,875
	<hr/>
Total	\$ 1,076,625

The above estimation is made for the wet grinding via Drais mill when producing about 100,000 gallons of minus 45 μm slurry fuel on-site for 100-hr full-scale engine testing. Assuming an average distance of 100 miles per trip, the freight charges will be \$20.00 per ton of coal. A coal pile area 2400 ft^2 with the base of about 60 ft. x 40 ft. will be required for the incoming coal storage. A conveyor will be used to transport coal into the crusher before the fine grinding. On-line production can minimize the storage of finished fuel and the tanker trucks required.

In the case of purchasing fuel from slurry manufacturing company, the 100-hr testing (100,000 gallons) would cost about \$1,014,200 based on the price of slurry at \$8.00 per gallon as estimated below:

Costs with Purchasing Fuel:

Fuel Cost (@ \$8.00/gallon)	\$ 800,000
Transportation Costs (to storage tanks and test site)	\$ 70,000
Storage Tank Costs/Installation	\$ 50,000
Labor and Utilities	\$ 2,000

	<hr/>
	Σ \$ 922,000
Others (@ 10%)	\$ 92,200

	<hr/>
Total	\$1,014,200

With purchasing the slurry from manufacturers, a huge or several slurry storage tanks near the engine test site with a total capacity of more than 100,000 gallons will be required. In addition, a total about 23 tanker truck loads would be needed to transport the finished slurry from the manufacturing site to the storage tanks. If the storage tanks do not locate nearby the test site, then the slurry will still need to be transported by tanker trucks to the combustor fuel system for the 100-hr engine testing.

Fuel Preparation - Initial and Finish Grinding

The laboratory task of initial and finish grinding was completed at AMAX R&D. The test data were analyzed and its results were used to develop the design and operating criteria for slurry fuel preparation, and to provide process cost information for the fuel cost projection spreadsheet.

In the initial grinding, it was found that changing either the loading or the viscosity had little effect upon grinding performance as long as the slurry was fluid (viscosity less than about 1,000 centipoise). The important fuel specification which impact the design and operation of the initial grinding circuits are the particle size distribution and the coal grindability. The test results of ball mill and rod mill followed the Bond equation as

$$W = W_i \left\{ \left[\frac{100}{P(80)} \right]^{0.5} - \left[\frac{100}{F(80)} \right]^{0.5} \right\} \quad (1)$$

where W is the energy applied in kWh per short ton and W_i is the "work index", a proportionality constant, specific for the material being ground. P(80) and F(80) are taken from the cumulative particle size distribution curves for the product and feed, respectively. The work index (W_i) for coal can be expressed by the Hardgrove grindability index (HGI),

$$W_i = \frac{435}{HGI^{0.81}} \quad (2)$$

Taken together, Equations 1 and 2 suggest that the capacity of a grinding circuit with a fixed amount of installed power should almost directly proportional to the HGI of the coal for the initial wet grinding operation.

In the finish grinding, stirred ball mills seem to be particularly effective for this type of grinding. Table 24 lists the source coals and the ranges of the operating variables investigated during the finish grinding tests. The test results of finish grinding by using a 40-liter Drafswerke stirred ball mill fitted well with the correlated Bond equation. The following equation predicts the amount of energy (W) required for grinding in a stirred ball mill in kWh per dry short ton of coal,

$$W = \frac{421.9}{HGI^{0.83}} \left\{ \left[\frac{100}{P(MMD)} \right]^{0.97} - \left[\frac{100}{F(MMD)} \right]^{0.97} \right\} f_{ball} \quad (3)$$

where P(MMD) and F(MMD) are the mass mean diameters of the product and feed particle size distributions, respectively. HGI is the Hardgrove grinding index of the coal and f_{ball} is the grinding media size efficiency factor. The ball size efficiency factor of grinding media is function of the mass mean diameter of the ball size and the mass mean diameters of the feed and product size distributions of the coal. The equation (Eq. 3) indicates that the feed grinding energy required is governed by the grindability of the coal and by the size of the grinding balls used in the mill.

Figures 44 and 45 show the relative effects of variations in the finished particle size specification and changes in the grindability of the coal on grinding capacity. The relative grinding capacity of the stirred ball mill increases with increasing the top size of product slurry. Similarly, the grinding capacity increases in a linear relationship as the Hardgrove grindability index of the coal increases. (The HGI of common coals are typically around 55 or 60 but can range between 40 and 100 with the higher index number denoting a more easily ground materials.) On the other hand, it appears that variations in solids loading, slurry viscosity, and dispersant addition do not have any significant effect upon the grinding performance of the stirred ball mill when operating within the normal range of conditions.

In general, the finish grinding step is more significant operation than the initial grinding step in terms of both capital costs and operating costs. Stirred ball mills used in the finish grinding are available in a number of configurations and from a number of manufacturers. Drafswerke advertises a 1,500-liter model which draws 2,000 horsepower that is believe to be the largest unit commercially available. Such a unit would have a capacity of about 20 tons of coal per hour in a typical micronized slurry fuel application. Multiple units are thus required to provide the capacity for the proposed multiple installations.

Full-Scale Testing Fuel

The first bulk lot (4500 gallons) of slurry prepared by AMAX R&D has been shipped to Peoria for the full-scale combustor testing. The slurry was delivered by a tanker truck and unloaded in an on-site fuel tank which has a capacity of about 6000 gallons and is equipped with an agitator. Figure 46 illustrates the fuel system of full scale combustor test facility. During the testing, slurry

Figure 44. Relative Capacity of Stirred Ball Mill Versus Nominal Top Size of Product Slurry. (Relative capacity = 1.0 when producing -45 μm slurry from -425 μm feed slurry)

Figure 45. Relative Capacity of Stirred Ball Mill Versus Hardgrove Grindability Index of Feed Coal. (Relative capacity - 1.0 when grinding coal with Hardgrove grindability index of 55)

Figure 44. Relative Capacity of Stirred Ball Mill Versus Nominal Top Size of Product Slurry. (Relative capacity = 1.0 when producing $-45\ \mu\text{m}$ slurry from $-425\ \mu\text{m}$ feed slurry)

Figure 45. Relative Capacity of Stirred Ball Mill Versus Hardgrove Grindability Index of Feed Coal. (Relative capacity = 1.0 when grinding coal with Hardgrove grindability index of 55)

Figure 46. Full-Size Combustor Tests: Fuel System

Concerns on the slurry fuel and flushing wastes handling during the full-size combustor testing are summarized:

1. Slurry Flushing Waste

The flushing liquids from fuel lines contain waste wash water and coal slurry. The coal particles in the liquids are dispersing well and not easily settling-down. Our past experience showed a flocculation agent is needed to be added to stimulate the solid-liquid separation before clean water can be discharged.

The flocculation procedures begin with adding dry alum or liquid alum, at 5.5 wt% on coal basis, to the waste slurry and stir well, allowing the waste slurry mixture settledown, and then decanting the clear supernatant water. The alum can be either the ammonium aluminum sulfate double salt or the straight aluminum sulfate. Alum forms aluminum hydroxide flocs in weakly acid and neutral water. These flocs are effective for coagulating the coal and precipitating the dispersant in the slurry. The followings show an example to treat 20 gallons of slurry waste with adding alum as a flocculation agent.

- For 20 gallons slurry waste through the fuel lines,
 Total slurry weight = 20 gallons x 10.01 lb/gallon = 200.2 lb
 Total coal content = 200.2 lb slurry x 54.1% coal loading = 108.3 lb
 Alum required = 108.3 lb coal x 5.5% alum concentration = 5.96 lb
- Dissolve this 5.96 lb of alum in 4 gallons of water before adding into the waste water tank.
 This is equivalent to 18 wt% solution in liquid alum form.
- Allow the waste slurry to settle for 24 hours and decant off the clear supernatant water. Remove the supernatant water from the tank by pumping the water down to just above the sludge line. The remaining sludge contains about 15 to 20% solids (1.5 to 1.8 lb coal per gallon).
- If needed, portland cement can be used to solidify the thickened sludge for the waste landfill.

2. Make-Up Water

Water evaporation from the slurry fuel could cause increases of coal loading and slurry viscosity. From a 6,000 to 7,000 gallon tank with 10 ft ID, an evaporation rate of 0.1 inch/day has been measured (based on the AMAX experience in the past). In our feed tank with a closed cover on the top, we do not expect a rate as great as that. However if slurry has to be stored for more than two weeks, the level of slurry fuel in the storage tank should be monitored periodically once a week with a long rod. When the slurry level loses more than a half inch (0.5 in.), a make-up water (24.5 gallons) needs to be added to keep the constant fuel properties.

$$\text{Make-up Water} = \pi \times 5^2 \times 0.5/12 = 3.27 \text{ ft}^3 = 24.5 \text{ gallons}$$

3. Slurry Recirculation

Upon the completion of a combustion run, the slurry lines are flushed with water wherever possible when shutting down the fuel system. In the case when slurry has to be stored for a long period of time (e.g., more than 2 weeks), then besides the low-speed agitation, pumping the slurry through the feed lines and recycling back to the fuel tanks are recommended. This can be carried out once a week for a period of one hour and the recirculation slurry lines do not need water flushing everytime.

4. Bottom Hard-Pack Cake

Under certain circumstances of tank agitator or recirculation failures, a hard pack of slurry could be built on the bottom of slurry tank. Also, depending upon each testing, a heel of slurry may be left in the bottom of the tank at the end of a campaign. This remaining slurry may be below the level of the agitator or the tank outlet to the recycle pump. A hard-pack cake could be developed and sometime difficult to be resuspended. If these happen, it is necessary to break up the bottom

hard-pack by forcing the compressed air into the cake through a long rod-tubing to promote mixing and stir up the content.

5. Agitator Selection

Properly designed agitators is needed to prolong the on-site storage time without coal particle settlement occurring. To prevent any detrimental effects on the coal-water slurry due to agitation, it is necessary to select an agitator that is highly efficient and imposes low shear to the fluid. Agitator design including motor, impeller, and another storage vessel variable, is directly dependent upon the rheological properties of the stored material, location of the inlet and outlet portals, and tank size. Turbulence in a stirred tank can be correlated with the impeller Reynolds number:

$$N_{Re} = \frac{A D^2 N \rho_f}{\mu}$$

where A = a constant dependent on agitator equipment; D = impeller diameter, m; N = rotational speed, rev/sec; ρ_f = fluid density, kg/m³; and μ = viscosity, kg/m-sec. When N_{Re} exceeds 10,000, flow is turbulent. Transitional flow occurs for N_{Re} between 10 and 10,000. If N_{Re} is less than 10, flow is laminar.

Based on the above consideration, an agitator with a motor size of 5 HP was identified. For a short storage period, a constant mixing will be carried out with an output constant speed about 23 RPM. However when slurry has to be stored for a long period of time, then the slurry would be required only periodic agitation with a speed about 150 RPM. Continuous vigorous agitation, particularly with vortex formation, should be avoided since the reagent balance may be adversely effected and air may become entrained in the slurry. Regular mixing, perhaps continuously by recycle pumping or operating the mixer at a slow speed or else intermittently by operating the mixer once for an hour or two each day under more vigorous conditions is adequate. This should prevent the formation of a hard-pack cake which could be difficult to resuspend.

Some other operating problems of fuel system may be encountered when the future additional loads are received and stored. Periodically, the slurry in the storage tank should be monitored for sedimentation at least once a week. An air lance is useful for manually resuspending a stubborn hard-pack cake, but one should avoid routine use of compressed air for mixing the slurry since bubbling air through the slurry, like intense agitation, could accelerate evaporation of water from the fuel and re-entrain air into the slurry that might change the slurry rheological properties.

Fuel Cost Assessment

The fuel cost projections are developed in a spreadsheet from the model which intends to calculate the baseline fuel cost for supplying slurry to a coal-fueled Centaur Model H cogeneration system. The spreadsheet is structured so that the cost effects of alternative operating scenarios may be examined using a common set of assumptions. The model has been calibrated against fuel costs projections made previously for similar type plants from 14.5 to 100 MW of capacity.

In our previous studies, the location of the fuel manufacturing plant with respect to the source of the coal and to the cogeneration site was found to have a significant effect upon the cost of fuel to the user. This is largely due to the difference in the cost of transporting lump coal as opposed to transporting slurry fuel. However, this difference also has an impact on the type of receiving, storage, and shipping facilities required at each site. The location of the fuel manufacturing also has an impact upon the salability of any middling products from the manufacturing process and the disposal of refuse from the plant. Locating the fuel manufacturing facility either at the coal mine or at the user's site allows sharing of some management and supporting staff functions which further reduces the cost of fuel production.

The resulting spreadsheet used to project the fuel cost for an on-site fuel preparation to supply slurry for single Centaur H engine is summarized in Table 25. The production cost of fuel in this case is projected at \$5.53 per million Btu. This cost covers any costs that the user incurs to receive, store and pump the coal slurry fuel to the burner. Labor, utilities, operating and maintenance supplies, and indirect costs (such as amortization), are also included. As usual, the on-site fuel cost largely depends upon the operating and maintenance costs, on-site indirect cost, and transport cost of feed coal. The ash content and coal loading of the fuel will only slightly impact the total fuel cost.

Table 25. Operating Cost Summary for CWM Fuel Plan at User Site

Capacity:	3.8 MW
Fuel Specification:	55% Solid 45 μ m Top Size 14 μ m MMD 7.0% Ash (dry basis) 0.8% Sulfur (dry basis)
Coal Price:	\$27/ton
Net Coal Cost: (w/freight)	\$1.15/MMBtu (LHV)
Operating & Maintenance:	\$2.44/MMBtu (LHV)
Indirect & Amortization:	\$2.52/MMBtu (LHV)
Total Fuel Cost:	\$6.11/MMBtu (LHV)

6. PHASE II - TASK 6 - HOT END SIMULATION

6.1 SPECIFIC ITEMS OF PROGRESS

- An RA330 shroud was installed inside the candle filter vessel to inhibit blinding of the candle. Corroded parts in hot valves were replaced with acid resistant components. Both modifications were made to increase long-term rig reliability.
- Electric heater coils were installed to add supplemental heat prior to material sample section to combat heat loss.
- Two new methods of mounting a candle to a tubesheet were designed and tested. Each incorporated a ceramic gasketing material to provide the gas tight seal.
- A conical primary zone and impactor section were developed and tested.

6.2 DISCUSSION

Efforts continued to prepare the Hot End Simulation Rig (HESR) for the initial 100-250 hour run of the 1000 hour test series. Several modifications were incorporated into the system and tested. A summary of Hot End Rig testing is shown in Table 26. Some of the system modifications include the installation of acid resistant parts in the system's hot valves, and a shield for the candle filter to prevent sticky, ash build-up on the candle element at the entrance to the filter vessel. Also, 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. Most recently, a conical primary zone and impactor section were designed and tested in the rig.

Acid resistant replacement parts for the filter bypass ball valves and the back pressure valve were installed. During earlier testing, in HESR-16, the exhaust temperature was running below the dew point of sulfuric acid, and was therefore the main contributor of valve deterioration. 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 be feasible due to the

Table 26. Summary of Hot End Simulation Rig Testing

Test No.	Objective	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	4:12	82	N/A	1.25
18	• Extended evaluation of interam mount	8:08	76	N/A	1.25
19	• Assess heater coils in material sample section	7:43	87	1167	1.23
20	• Assess modified cup/candle mount assembly	4:03	82	N/A	1.20
21	• Evaluate ceramic wool in cup assembly	4:09	87	N/A	1.15
22	• Evaluate ceramic wool in cup assembly	3:58	85	N/A	1.15
23	• 100 hour material evaluation	5:00	83	949 ¹	1.19
24	• 100 hour material evaluation	13:30	86	1292 ¹	1.22
25	• Evaluate conical primary zone and injector section	4:01	82	762	1.22
26	• Assess modified sample section heating	3:20	80	772	1.23
27	• Assess modified sample section heating	3:27	80	816 ²	1.19
28	• Assess modified sample section heating	4:00	81	816 ²	1.19
¹ Temperatures measured with electric heaters installed. ² Recorded temperatures were measured with torch installed prior to material sample section. However, temperatures were observed to read 1600°F+ when torch was ignited.					

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-laden, 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 for these electric heaters.

For the candle filter vessel a shroud of RA-330 was fabricated and installed at the inlet of the 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 test 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 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. The following test would expose the new mount more rigorously.

HESR-18 tested the new candle mount 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.

The material sample section heaters and associated spool piece were received; 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 is only Inconel.

HESR-19 was run to assess the heater coils. 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 malfunction. 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 material necks down. 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 47 shows the heater coil installed in the spool piece. Figure 48 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.

Figure 47. Heater Coil Prior to Material Samples

Figure 48. Heater Coil With Dusting of Particulate.

The mount and plug were modified for HESR-20, which was run without materials 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 this 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 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 49. 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 mounting system was successful.

At this point in testing, three methods of mounting a candle to a tubesheet have 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 have failed with this type of mount, however, it is not 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 provides some cushioning or shock-absorption of the candle which extends the candle life. This mount is the favored method at the present time.

Figure 49. Candle Filter Mount

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 has 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 cools, a hard, brittle substance is formed, and has been seen in previous tests. This matter can be easily removed. Since the candle experienced no physical degradation, it will be reused.

A continuity check of the heaters revealed that the aft one was burnt out. The heaters have been removed from the spool and a new method of heating the material samples is being 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 50, 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 does 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 can accumulate in the crucible partially filling the increased volume. Although the residence time will shorten over the course of the run due to the accumulation of slag, this will not significantly affect combustor performance because of the increased impactor spool volume and inherently low flow rate. To decrease downtime, the slag filled crucible can be easily removed after a run, and a new one installed.

Figure 50. Conical Primary Zone and Impactor Section

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 is 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 can be easily removed.

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

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.

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 consists of 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 is used to mix with the air and ignite in the hot, coal combustion exhaust. Once the diesel supply is expended, the natural gas would easily ignite 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. The natural gas orifice will be modified and a evaluation test will be performed prior to the beginning of the 100-250 hour run.

In summary, long-term rig reliability has been improved. A conical primary zone and Impactor section have been developed and tested to allow for slag accumulation during 250-hour tests. A candle filter shroud protects the element from direct impingement of particulate, which previously led to blinding of the candle. A flexible candle mount system has been established and has been successful during extended testing. Supplemental heating of the material sample section is currently being modified and is the objective of the next HESR test. Once the sample section torch heating is demonstrated effectively, the 1000 hour test series will begin.

7. PHASE III - TASK 1 - DESIGN

7.1 SPECIFIC ITEMS OF PROGRESS

- Design of the engine parts required to integrate the combustor island started.

7.2 DISCUSSION

Some preliminary work was done in Phase III to determine the best way of obtaining the necessary parts to provide the ducting required to integrate the combustor island with the generator. The design of a steam cooled turbine inlet duct has begun. It was planned to use the outer housings from an earlier version of the Centaur and modify them to fit the Type H Centaur. One of the housings may have to be fabricated. The interface between these parts and the ducting is being studied. The turbine inlet scroll will be steam cooled in order to accommodate the required turbine inlet temperature of approximately 1920°F and to trim the radial inlet temperature profile. Planning and selection of equipment for the engine test site is also in progress.

APPENDIX A

Appendix A contains CWM slurry fuels which have been tested at Solar's combustor rigs (TSSC, IBSTF, and HESR) and full-scale combustor. The slurry fuel properties, coal source, particle size, and ash composition and fusion temperature are listed for each tested fuel. The majority of slurries were formulated with the blend of eastern Kentucky coals, except few coals have been used for special testing purposes. Different batch name was referred to each preparation and shipment.

Coal	C	D	E	F	G	H
Source	80% Kentucky 5 20% Elkhorn	80% Kentucky 5 20% Elkhorn	Splint	Powhatan	Powhatan with 5.3% Lime	75% Clean Elkhorn 25% Reed Elkhorn
Coal content (wt%)	54.10	56.50	55.50	60.00	48.80	54.09
Ash Content (wt%)	2.10	1.29	1.70	3.40	7.50	1.25
Particle Content						
% Passing 100 micron	100.00		99.80	100.00	100.00	
% Passing 74 micron		98.10	99.70	100.00	100.00	
% Passing 48 micron			98.00	98.50	98.50	98.90
% Passing 37 micron			71.60	98.70	98.70	98.60
% Passing 25 micron			63.70	98.50	98.50	98.30
% Passing 15 micron			55.40	74.00	74.00	80.20
% Passing 5 micron			24.00	38.00	38.00	55.60
% Passing 4 micron						44.70
% Passing 3 micron						33.90
% Passing 2 micron						26.87
% Passing 1 micron						17.50
Mean Size (micron)	14.10	21.00	21.00	11.50	11.50	9.10
Slurry Viscosity (cp)						
@ 100/sec	300.00	330.00	350.00	350.00	300.00	225.00
@ 1000/sec		275.00	400.00	700.00	250.00	425.00
Slurry (Btu/lb)	7030	7801	7616	7758	6190	7245
Proximate Analysis (wt%)						
Ash	3.88	2.23	3.03	5.52	13.82	2.30
Volatiles	38.10	34.80	37.40	37.51	38.43	31.70
Fixed Carbon	60.02	62.97	59.57	56.97	47.74	66.00
Ultimate Analysis						
Carbon	77.10	84.18	81.20	81.44	83.38	85.82
Oxygen	14.38	8.36	8.45	8.68	6.16	7.35
Hydrogen	5.80	5.26	4.91	5.25	5.67	5.08
Nitrogen	1.82	1.84	1.51	1.50	1.53	1.15
Sulfur	0.90	0.56	0.60	3.13	3.26	0.59
Ash Composition						
SiO ₂	53.00	40.30	44.80	42.80	13.80	53.50
Al ₂ O ₃	28.10	28.00	25.70	22.80	7.60	21.20
Fe ₂ O ₃	11.60	18.20	18.80	20.90	7.10	10.90
CaO	1.36	5.02	5.18	1.91	18.20	4.00
MgO	0.61	1.10	1.39	0.42	11.40	0.05
Na ₂ O	0.91	1.78	0.30	0.59	1.21	2.60
K ₂ O	1.03	0.30	0.31	1.30	0.49	1.30
TiO ₂	2.07	1.67	1.50	1.11	0.33	1.00
MnO ₂	0.07	0.07	0.02	0.05	0.04	
P ₂ O ₅	0.31	0.48	0.67	0.63	0.04	0.20
V ₂ O ₅	0.06	0.07	0.05	0.05	0.02	
PbO	0.04	0.05	0.03	0.05	0.01	
Ash Fusion Temperature (°F)						
Oxidizing/Reducing						
Initial Deformation	2670/2460	2368/2233	2395/2140	3482/2485	2512/2000	2515/2250
Softening	+2700/2605	2363/2286	2530/2275	2502/2480	2544/2183	2665/2275
Hemispherical	+2700/2650	2521/2356	2450/2305	2518/2487	2558/2351	+2700/2350
Fluid	+2700/2700	2555/2484	2518/2485	2518/2485	2583/2440	+2700/2610

Coal	I	J	K	L	M	N
Source	80% Kentucky 5 20% Elkhorn	80% Kentucky 4A 20% Elkhorn	80% Kentucky 4A 20% Elkhorn	80% Kentucky 4A 20% Elkhorn	Clean Elkhorn	80% Kentucky 4A 20% Elkhorn
Coal content (wt%)	55.10	54.00	54.10	54.50	53.93	54.58
Ash Content (wt%)	2.15	2.11	2.15	2.18	1.78	2.21
Particle Content						
% Passing 100 micron	99.90		100.00			
% Passing 74 micron	99.90		100.00	100.00		
% Passing 45 micron	97.50	99.40	99.40	99.50	100.00	99.00
% Passing 37 micron	96.70	99.10	99.30	99.10	100.00	98.50
% Passing 25 micron	93.40	99.00	99.00	99.00	99.90	99.90
% Passing 15 micron	39.20	73.30	50.00	68.40	91.80	75.90
% Passing 5 micron	22.90	37.30	34.30	37.10	85.20	42.10
% Passing 4 micron		30.00			54.40	31.20
% Passing 3 micron		21.00			40.90	23.20
% Passing 2 micron		15.90			31.90	15.10
% Passing 1 micron		8.90			21.50	4.10
Mean Size (micron)	14.00	14.00	9.80	12.80	7.50	9.70
Slurry Viscosity (cp)						
@ 100/sec	450.00	470.00	300.00	375.00	300.00	325.00
@ 1000/sec	300.00	568.00			370.00	435.00
Slurry (Btu/lb)	7268	7084	7043	6975	7156	7064
Proximate Analysis (wt%)						
Ash	3.88	3.88	3.97	4.00	3.26	4.05
Volatiles	35.56	36.52	34.90	37.60	32.67	35.87
Fixed Carbon	60.56	59.60	61.20	58.40	65.03	60.08
Ultimate Analysis						
Carbon	84.05	83.84	83.97	83.71	85.29	83.24
Oxygen	7.94	8.96	7.61	8.09	7.07	8.11
Hydrogen	5.61	5.43	5.64	5.62	5.28	5.90
Nitrogen	1.58	1.02	1.92	1.86	1.63	2.19
Sulfur	0.82	0.85	0.88	0.72	0.73	0.86
Ash Composition						
SiO ₂	48.50	52.90	42.60	47.60	49.90	44.60
Al ₂ O ₃	29.20	28.00	26.50	27.03	25.10	22.80
Fe ₂ O ₃	15.00	6.65	17.50	15.01	11.00	18.90
CaO	1.74	2.32	1.67	2.53	2.40	3.00
MgO	0.58	0.57	0.59	0.55	0.90	0.01
Na ₂ O	1.38	1.67	2.37	1.55	1.90	1.50
K ₂ O	1.19	1.23	2.05	0.90	1.90	0.90
TiO ₂	1.45	1.20	1.13	1.15	0.90	1.30
MnO ₂	0.05		0.04			
P ₂ O ₅	0.51	0.19	<0.06	0.20	0.20	0.30
V ₂ O ₅	0.04		0.06			
PbO	<0.12		<0.12			
Ash Fusion Temperature (°F)						
Oxidizing/Reducing						
Initial Deformation	2385/2415	2485/2375	2480/2180	2645/2450	2580/2205	2490/2144
Softening	2650/2475	+2700/2700+	2620/2190	+2700/2490	2650/2295	2661/2345
Hemispherical	2690/2515	+2700/2700+	2630/2300	+2700/2550	2670/2325	2669/2419
Fluid	2700/2605	+2700/2700+	2690/2580	+2700/2595	2687/2632	2676/2491

Coal	O	P	Q	R	T
Source	50% Kentucky 4A 50% River Queen	51% Kentucky 4A 49% River Queen	Kentucky 4A	Kentucky 4A	Kentucky 4A Elkhorn
Coal content (wt%)	54.18	53.45	51.0	54.34	54.36
Ash Content (wt%)	2.15	2.19	1.97	2.07	1.85
Particle Content					
% Passing 100 micron			99.83		
% Passing 74 micron		99.95	99.81	99.77	99.79
% Passing 45 micron	99.60	99.43	98.70	99.06	98.83
% Passing 37 micron	99.50	99.03	98.29	98.51	98.16
% Passing 25 micron	98.00	91.90	93.45	97.91	94.86
% Passing 15 micron	85.50	90.15	68.48	75.18	75.08
% Passing 5 micron	50.40	59.70	36.20	41.06	41.04
% Passing 4 micron	39.40	41.89	26.12	29.42	29.35
% Passing 3 micron	29.00	34.45	19.34	22.98	22.30
% Passing 2 micron	18.00	23.98	12.64	15.37	14.65
% Passing 1 micron	3.50	10.52	3.56	5.39	4.48
Mean Size (micron)	8.00	7.60	12.60	10.40	10.87
Slurry Viscosity (cp)					
@ 100/sec	300.00	300	310	150	275
@ 1000/sec	400.00	340	178	190	300
Slurry (Btu/lb)	7013	6868	6641	7174	7238
Proximate Analysis (wt%)					
Ash	3.93	4.05	3.84	3.90	3.01
Volatiles	38.01	38.78	37.32	34.82	34.58
Fixed Carbon	58.06	57.17	58.84	61.28	62.41
Ultimate Analysis					
Carbon	82.23	81.30	82.52	84.09	84.40
Oxygen	8.85	9.53	11.51	7.66	7.78
Hydrogen	5.68	5.51	3.88	5.56	5.53
Nitrogen	1.80	1.82	1.85	1.78	1.68
Sulfur	1.44	1.84	0.43	0.92	0.61
Ash Composition					
SiO ₂	50.60	48.02	52.04	46.49	42.56
Al ₂ O ₃	23.10	26.36	31.73	28.31	26.59
Fe ₂ O ₃	13.80	16.75	8.2	12.00	13.80
CaO	2.70	1.56	2.9	4.16	5.17
MgO	0.01	0.56	0.39	0.79	0.59
Na ₂ O	1.20	0.88	1.21	1.20	1.44
K ₂ O	1.30	1.83	1.01	0.96	0.85
TiO ₂	1.30	1.14	1.16	1.09	1.03
MnO ₂					
P ₂ O ₅	0.20	0.23	0.96	0.16	0.14
V ₂ O ₅					
PbO					
Ash Fusion Temperature (°F)					
Oxidizing/Reducing					
Initial Deformation	2637/2070	2548/2399	+2700/2602	2672/2387	2422/2287
Softening	2700/2190	2656/2447	+2700/2685	2694/2419	2640/2355
Hemispherical	2700/2270	2665/2463	+2700/2700+	+2700/2467	2684/2425
Fluid	2700/2474	2673/2486	+2700/2700+	+2700/2651	2680/2467

Coal	U	V	W
Source	Kentucky 4A/Blue Gem	Kentucky 4A/Elkhorn	Kentucky 4A/Elkhorn
Coal content (wt%)	54.0	54.48	54.1
Ash Content (wt%)	2.10	2.99	2.94
Particle Content			
% Passing 100 micron	99.95	99.97	99.95
% Passing 74 micron	99.59	99.93	99.88
% Passing 45 micron	98.45	99.37	98.71
% Passing 37 micron	97.51	98.63	98.25
% Passing 25 micron	82.99	72.19	81.55
% Passing 15 micron	68.97	60.73	66.95
% Passing 5 micron	37.18	27.21	40.23
% Passing 4 micron	27.50	18.07	29.58
% Passing 3 micron	20.85	12.51	22.58
% Passing 2 micron	13.76	7.46	14.68
% Passing 1 micron	4.38	1.83	4.50
Mean Size (micron)	12.2	14.1	11.9
Slurry Viscosity (cp)			
@ 100/sec	200	250	210
@ 1000/sec	285	345	305
Slurry (Btu/lb)	7094	7110	7064
Coal Characteristics			
Proximate Analysis (wt%)			
Ash	3.84	5.43	5.37
Volatiles	38.41	34.61	34.33
Fixed Carbon	59.75	59.98	60.30
Ultimate Analysis			
Carbon	79.51	83.82	84.16
Oxygen	12.39	8.19	8.00
Hydrogen	5.47	5.48	5.60
Nitrogen	1.71	1.56	1.48
Sulfur	0.92	0.94	0.76
Ash Composition			
SiO ₂	46.49	34.90	35.10
Al ₂ O ₃	28.89	25.49	23.40
Fe ₂ O ₃	18.14	27.27	30.70
CaO	2.64	1.29	1.20
MgO	0.24	0.55	0.53
Na ₂ O	1.17	0.92	0.63
K ₂ O	1.12	1.11	1.08
TiO ₂	0.93	1.14	1.15
MnO ₂			0.13
P ₂ O ₅	0.18	0.01	<0.01
V ₂ O ₅			0.05
PbO			<0.01
Ash Fusion Temperature (°F)			
Oxidizing/Reducing			
Initial Deformation	2175	2527/2115	2530/2073
Softening	2211	2588/2143	2591/2161
Hemispherical	2496	2632/2210	2600/2269
Fluid	2830	2649/2524	2655/2497

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