1 of 1

Advanced Coal-Fueled Industrial Cogeneration Gas Turbine System -- Combustion Development

Topical Report

R. T. LeCren

June 1994

Work Performed Under Contract No.: DE-AC21-86MC23166

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

By
Solar Turbines, Inc.
San Diego, California

MASTER

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CONTENTS

<u>Section</u>		<u>Page</u>
	ABBREVIATIONS AND SYMBOLS	1
1.0	INTRODUCTION	2
2.0	ACHIEVEMENTS	3
3.0	DISCUSSION	4
	3.1 Combustor Performance Development	4
	3.2 Slag Removal	6
	3.3 Crude Oil Evaluation	17
	3.4 Sulfur Oxide Removal	22
	3.5 Fuel Property specification Testing	40
	3.6 Injector Development	60
4.0	CONCLUSIONS	63
5.0	RECOMMENDATIONS	64
	REFERENCES	65
	APPENDIX A	66

FIGURES

<u>Figure</u>		<u>Page</u>
1	Baseline Combustor Deficiencies	4
2	Coal Combustor Model - 1X	5
3	Primary Zone Design Modifications	5
4	Water-Flushed Slag Pit	7
5	Baseline TSSC With Water-Quenched Slag Pit	10
6	Slag Test Geometries Tested	11
7	Slag Removal System	13
8	TSSC Test Configuration for Evaluation of Fuels of Varying Properties	17
9	Primary Injector Section After the TSSC Crude Oil Test	18
10	A) Hole Near Weld on Primary Zone Injector; B) Injector Face	19
11	Effects of Varied Air Assist Pressure on NO _x	21
12	Combustor Performance Shown by Primary Zone Equivalence Ratio vs. Measured Oxygen in the Effluent	21
13	Sorbent Injection Experimental Test Set-up	24
14	Dense-Phase Pneumatic Sorbent Feed Tank	25
15	SO ₂ Reductions for Dolomite Injected in the Secondary Zone	26
16	Actual Measured SO ₂ Levels at Varying Dolomite Injection Rates Compared to Theoretical SO ₂ Levels Based on Fuel Sulfur Content With No Sorbent Injection	27
17	Raw Powdered Dolomite	29
18	Sorbent/Ash Particulate Collected in Test No. 5	30
19	SEM Analysis of "Glassy" Spheroid in Particle Sample	31
20	Sorbent Screw Feeder	31

FIGURES (Continued)

Figure		Page
21	Sorbent Screw Feeder Atmospheric Calibration	32
22	SO ₂ Emission Reductions for Dolomite Injection in the Secondary Zone	36
23	Comparison of SO ₂ Reduction for Three Calcium Sorbents Injected into the Secondary Zone of the TSSC Burning a CWM with 1.4 wt% Sulfur	36
24	Comparison of SO ₂ With Varying Injection Rates of Three Sorbents Into the Secondary Zone of the TSSC	37
25	SO ₂ Reduction of Dolomite Injected in the Secondary Zone of the TSSC Burning CWMs of Varying Sulfur Loading	39
26	SO ₂ Emissions at Varying Ca/S Ratios of Dolomite Injection	39
27	Comparison of SO ₂ Reductions of Dolomite of Varying Sizes Injected into the Secondary zone	42
28	TSSC Test Configuration for Evaluation of Fuels of Varying Properties	42
29	Outlet Temperature Profile of TSSC Burning CWMs of Varying Coal Loadings	49
30	NO _x Emissions of TSSC Burning CWMs of Varying Coal Loadings	49
31	Variation of Outlet Temperature With Fuels of Varying Coal Ash Concentration	52
32	Variation of NO _x Emissions With Fuels of Varying Coal Ash	53
33	Outlet Temperature and Emission Characteristics of TSSC Burning CWMs Made From Coals of Varying Particle Size	56
34	Outlet Temperature and Emission Characteristics of TSSC Burning CWMs Made From Coals From Different Seams	58
35	CWM Fuel Injector With Baseline and Modified Air Assist/Fuel Tip	61
36	Drop-Size Characteristics of 600 pph Injector	61

TABLES

<u>Table</u>		<u>Page</u>
1	Summary of TSSC Combustor Testing	8
2	Slag Tap Heating in Atmospheric Tests Firing Slag Tap Torches Only	12
3	Summary of CWM Testing of Fuels of Varying Properties	14
4	Summary of TSSC Combustor Testing of Slag Removal System	16
5	Emissions Data From TSSC Crude Oil Test 2	20
6	Particulate analysis of Sample Collected in Test No. 500 With Dolomite Injection	28
7	Chemical and Physical Analyses of Calcium-Based Sorbents Used in Recent Tests	33
8	Analyses of Calcium-Based Sorbents	34
9	Result of Combustor Performance With Three Sorbents Injected into Secondary Zone	35
10	Properties of Dolomite of Different Grinds	41
11	Properties and Compositions of Combustion Testing Fuels	43
12	Summary of CWM Testing of Fuels of Varying Properties	44-45
13	Particulate Sample Analyses From Test Completed in TSSC With CWMs of Varying Fuel Properties	46-47
14	Slurry Properties for Full-Scale Combustor Testing	60
15	Results With Modified Air Assist and Fuel Tip Assembly	62

ABBREVIATIONS AND SYMBOLS

AMAX	Amax Research & Development Center
CFC	Coal fueled Centaur
CSC	Component Screening Combustor
CWM	Coal-Water Mixture
DCFGT	Direct Coal Fired Gas Turbine
HESR	Hot End Simulation Rig
IBSTF	Integrated Bench Scale Test Facility
PRIS	Particulate Removal Impact Separator
SEM	Scanning Electron Microscopy
TSSC	Two Stage Slagging Combustor
cp	centipoise
sec ⁻¹	
F/S	full size
LHV	over heating value
MMBtu	million British Thermal Units (based on Lower Heating Value)
MMBtu/hr	million British Thermal Units per hour (based on Lower Heating Value)
MW	mega watt
PHI	equivalence ratio
P _{in}	inlet air pressure
pph	pounds per hour
ppm	parts per million
ppmm	parts per million by mass
ppmv	parts per million by volume
psig	pounds per square inch gauge
T _{in}	inlet air temperature
T _{outlet}	secondary combustor outlet temperature
T _{PRIS}	PRIS temperature
μm	micron

Note: Gaseous emissions (NO_x, CO, UHC, & SO₂) are quoted in parts per million by volume corrected to 15% oxygen in the exhaust on a dry basis unless otherwise specified.

1.0 INTRODUCTION

This topical report summarizes the combustor development work accomplished under the subject contract. The objective was to develop a combustion system for the Solar 4MW Type H Centaur gas turbine generator set which was to be used to demonstrate the economic, technical and environmental feasibility of a direct coal-fueled gas turbine in a 100 hour proof-of-concept test. The development was carried out using two different scale combustors and three different test rigs. The initial design was carried over from previous contracts (DE-AC21-83MC20229, Low Emission Combustor and DE-AC21-84MC21284, Component Screening Fuel Flexible Combustor). The test combustor during the previous contract was a 1/10th scale of that required for the Type H Centaur gas turbine generator set. The initial objective was to solve operational problems encountered with this combustor and then scale the design up to full size. Before the contract was curtailed a full size system (primary zone, particulate removal system and secondary zone) was designed, fabricated, installed in a test facility at Caterpillar Tech Center and preliminary testing accomplished. At this point some problems existed but solutions were in hand and preparations for a 100 hour proof-of-concept engine test had begun.

This program started with a design configuration derived during the CSC program. The design went through the following evolution: CSC design which had some known shortcomings, redesigned CSC now designated as the Two Stage Slagging Combustor (TSSC), improved TSSC with the PRIS evaluated in the IBSTF, and full scale design. Supporting and complimentary activities included computer modelling, flow visualization, slag removal, SO_x removal, fuel injector development and fuel properties evaluation. Three combustor rigs were utilized: the TSSC, the IBSTF and the full scale rig at Peoria. The TSSC rig, which was 1/10th scale of the proposed system, consisted of a primary and secondary zone and was used to develop the primary zone performance and to evaluate SO_x and slag removal and fuel properties variations. The IBSTF rig which included all the components of the proposed system was also 1/10th scale except for the particulate removal system which was about 1/30th scale. This rig was used to verify combustor performance data obtained on the TSSC and to develop the PRIS and the particulate removal system. The full scale rig initially included the primary and secondary zones and was later modified to incorporate the PRIS. The purpose of the full scale testing was to verify the scale up calculations and to provide a combustion system for the proof-of-concept engine test that was initially planned in the program.

2.0 ACHIEVEMENTS

- **Stable and efficient combustion burning coal-water mixtures using the Two Stage Slagging Combustor.**
- **Molten slag removal of over 97% using the slagging primary zone and the particulate removal impact separator**
- **The feasibility of on-site CWM preparation was demonstrated on the subscale TSSC.**
- **A continuous slag removal system was tested on the scale combustor providing design information for the full size configuration.**
- **Completed an evaluation of coal-water mixture properties on combustor performance**
- **A water-cooled impactor was evaluated on the subscale TSSC.**
- **Four tests were completed on the full size TSSC, the last one incorporating the PRIS.**
- **A prototype design of an effervescent fuel injector was completed by Solar using design guidelines developed by Purdue. A set was ordered and tested.**
- **A target fuel specification was established and a fuel cost model developed which can identify sensitivities of specification parameters.**

3.0 DISCUSSION

3.1 COMBUSTOR PERFORMANCE DEVELOPMENT

The combustor tested in the Component Screening Combustor Program had two major shortcomings as shown in Figure 1. Slag would flow up the top cone through the transition and into the secondary. It was theorized that this slag would be captured by the PRIS when it was incorporated but would increase the amount of slag to be captured. The second problem was the escape of unburned fuel by way of a secondary recirculation zone as shown. This fuel would only partially burn in the secondary zone and therefore would result in reduced combustion efficiency.

To solve these two problem areas computer modelling and flow visualization were employed. A computer program called INTERN was utilized to analyze the problem and to suggest solutions. The CSC/TSSC design was not conventional in that the inlet and exhaust were at the same end which was different from the configuration that INTERN was developed for. However the input was modified to allow meaningful results to be obtained. Figure 2 is a sample output. Plexiglass models were constructed for flow visualization. Neutral density helium-filled soap bubbles were utilized as tracers. Both still and high speed photography were used to document the observations. Video recordings were also made.

Three configurations which were studied are shown in Figure 3. The approaches were essentially the same in each and that was to move the accelerating exit from the primary zone away from the point of injection. In configuration No. 1 the approach was to raise the top wall or cone so that the slag would not accelerate into the transition and fuel in the secondary recirculation would react before reaching the exhaust. Configuration No. 3 was similar to No. 1 except for the angled walls

Figure 1. Baseline Combustor Deficiencies

Figure 2. Coal Combustor Model - 1X

Figure 3. Primary Zone Design Modifications

below the plane of the injectors. This change was found to intensify the main recirculation patterns which improved slag capture. The approach in Configuration No. 2 was to utilize a single injector and move the exit from the primary to the outer edge. The use of a single injector eliminated the need to align multiple injectors to obtain a single downward flowing jet. Relocation of the exits removed the need for the exiting gases to flow over or near the incoming flow thus minimizing the possibility of unburnt fuel escaping. Of the three Configuration No. 3 was the most promising.

Tests were run to compare the three configurations. All were an improvement over the baseline with No. 3 better than No. 1 and No. 2 comparable to No. 3. During this series of tests the full size combustor was being designed. Both single and four injector configurations were considered. The design fuel flow for the TSSC was 600 pph. Since the full size combustor was 10 times larger the design fuel flow was 6000 pph. The fuel flow per injector for the 4 injector TSSC was 150 pph, for the single injector TSSC - 600 pph, for the 4 injector full size combustor - 1500 pph and for a single injector full size combustor - 6000 pph. During the injector development it was determined that satisfactory performance with a 6000 pph injector was difficult to attain, while it was with a 1500 pph injector. Since the purpose of the TSSC testing was to support the full size design all testing with a single injector TSSC was halted. Almost all of the testing described in Sections 3.2 through 3.5 was done with a four injector TSSC having conical walls as shown in Figure 3.

3.2 SLAG REMOVAL

Since 60-70% of the mineral matter in the coal would be removed in the primary zone of the TSSC a viable continuous slag removal system was needed. Design and testing of candidate removal systems was carried on in the subscale TSSC. The development path for continuous slag removal was to 1) assess the impact on combustor performance of a water bath located below the slag tap, 2) determine the properties of the slag collected in the water bath, and 3) design and test a continuous slag removal system.

At the outset of this work the design of the slag system was narrowed to two alternatives. Both designs had a water bath for quenching the slag and a lock hopper arrangement for slag removal. The designs differed in that one had a slag auger/crusher and the other did not. The first two parts of the development path listed above were completed to make a decision between these two design alternatives. Testing was completed in a series of four tests (Nos. 38, 39, 45 and 46). The first two tests were aimed at determining the impact of a water bath on combustor performance and the properties of the quenched slag. This testing indicated that the presence of a water bath has no impact on combustor performance and that the slag collected in the bath is generally in the form of crushable pellets. With this information it was determined that a slag/auger crusher would not be necessary. Testing was conducted on a simple lock hopper arrangement. Key results indicated that rapid purging of the water and slag through a valve is possible and that this process has no detectable impact on the combustor operation. The one remaining area pursued was efficient slag tap heating.

Testing started with a water quenched slag pit attached to the baseline TSSC. The combustor with the water quenched slag pit is pictured in Figure 4. The slag pit had a refractory lined upper half and exposed steel case on the bottom. The slag tap hole was 4 inches in diameter. Three of Solar's Saturn engine torches were used to heat the slag tap hole to prevent freezing and blockage. The torches burn natural gas and air from sources independent of the combustion air. Water was introduced through the upper pipe and exited through the lower pipe. The water was circulated to prevent boiling. The water level was controlled manually by watching the 12 thermocouples located

Figure 4. Water-Flushed Slag Pit

immediately above and below the water line. The water flow rate was 3 to 5 gpm through the slag pit. Water that exited through the outlet pipe passed through a filter to collect any particulate and slag that was entrained.

The system was operated on CWM in both TSSC Test Nos. 37 and 38. In Test No. 37 the combustor was operated at 40 psig for 3 hours on diesel fuel and then switched over to CWM burning a total of one barrel. Test 38 was operated at 80 psig over a longer time burning a total of four barrels of CWM. Test conditions and results are summarized in Table 1. In both tests the combustor ran very well with no noticeable influence from the water in the slag pit. The three slag tap torches were run continuously to maintain a high slag tap temperature. The temperature of the water entering the slag pit was steady at 80° F and the water exiting never climbed above 110° F indicating the likelihood of excessive water vaporization was low. The emissions were typical of tests with the baseline TSSC.

Materials collected in the water bath from these tests were analyzed and divided into four categories. In the two tests the majority (80%) of the material was in the form of slag pellets approximately 0.25 inch long. These pellets can be crushed by hand. The pellets are 99.8% ash and 0.2% carbon. Slag was also collected in the form of aggregates (15%) with a mean size of 0.25 to 0.5 inches and no dimensions larger than 1 inch. This material was also 99.8% ash and 0.2% carbon. The remaining slag pit contents were unburned carbon which was 90.5% carbon and 9.5% ash. The unburned carbon was in the form of large "briquettes" and fine dust. It should be noted that in Test No.38 all the material was in the form of slag pellets.

This data indicated that all the material collected in the slag pit was small enough to be successfully handled by a valve and lock hopper arrangement. A subscale unit was designed and fabricated for test. In this design a three inch ball valve was used to fill a lock hopper with periodic flushes of the slag pit contents. The system, illustrated in Figure 5, featured a torch heated slag tap hole, a water bath, a discharge pipe, an isolation ball valve, and a lock hopper. During combustor operation the slag removed from the primary zone flowed through the slag tap hole and dripped into the water

Table 1. Summary of TSSC Combustor Testing

Test Facility	TSSC	TSSC	TSSC	TSSC	TSSC	TSSC	TSSC
Test No.	34	35	36	37	38	39	40
Objective	Sorbent Evaluation	Sorbent Evaluation	Sorbent Evaluation	Slag Removal	Slag Removal	Single Removal	Single Injector
CWM*	'F'	'F'	'G'	'N'	'N'	'N'	'N'
T _{in} (°F)	620	650	631	604	627	615	637
P _{in} (psig)	75	74.6	74.3	73.3	74.0	74	74
T _{exit} (°F)	1806	1840	1657	1629	1801	1850	1659
Φ _{primary}	1.30	1.29	1.06	1.20	0.91	1.25	1.20
NO _x (ppm) (lbm/MMBtu)	87.5 (0.3747)	88.5 (0.3767)	114.1 (0.5078)	124.9 (0.5069)	121.0 (0.4914)	186 (0.6823)	147 (0.5901)
CO (ppm) (lbm/MMBtu)	12.9 (0.0350)	9.0 (0.0230)	10.1 (0.255)	41.0 (0.1014)	16.5 (0.04806)	150 (0.3711)	90 (0.22)
SO _x (ppm) (lbm/MMBtu)	549.1 (3.2692)	653.1 (3.9302)	648.7 (4.0210)	—	73.6 (0.4480)	187 (1.0719)	165 (0.923)
ΔP/P Primary (%)	4.1	3.9	4.2	4.1	3.9	4.1	4.2
Carbon Conversion	98.9	98.6	—	99.2	—	96.0	—
Slag Capture (wt%)	84	84	45	—	32.0	—	—
Heat Input (MMBtu/hr)	4.17	4.10	4.12	2.28	3.97	4.00	4.19

*See Appendix A for test fuels data.

bath, freezing instantaneously. The water bath had both inlet and outlet pipes for continuous water circulation to prevent boiling. Slag collected in the water bath sank to the bottom of the discharge pipe. After a given time period the isolation valve was rapidly opened and closed to fill the lock hopper with water and slag. The lock hopper could be charged with air pressure to control the pressure drop taken across the isolation valve.

The test hardware was designed to fit the existing TSSC rig which required that a very tight height requirement be placed on the slag removal system. The discharge pipe axis was at a right angle to the combustor centerline. One end of the discharge pipe was capped and the other was connected to the lock hopper with an isolation valve in between. In the full scale combustor a lock hopper can be positioned directly beneath the water bath and isolation valve without the need for a discharge pipe. Therefore, the full scale design should be more effective in removing all the slag collected in the water bath than this subscale hardware. If the subscale hardware could be proven to effectively remove slag than the scaled design would be even more effective.

The isolation valve and lock hopper arrangement was run in two tests. TSSC Test Nos. 45 and 46 were run at typical test conditions burning CWM 'T'. The combustor ran well with key operating parameters listed in Table 1. The tests were run for slightly less than two hours on CWM. The slag tap torches were operated throughout the tests while burning CWM. The isolation valve on the lock hopper was opened and the slag pit was purged eleven times in both tests. The purge operation was completed without any noticeable impact on the system while looking at such operating parameters as primary zone pressure, outlet temperature, and emission traces. Slag tap

Table 1. Summary of TSSC Combustor Testing (Continued)

Test Facility	TSSC	TSSC	TSSC	TSSC	TSSC	TSSC
Test No.	41	42	43	44	45	46
Objective	Single Injector	Single Injector/Sorbent	CWM Properties	CWM Properties	Slag Removal	Slag Removal
CWM*	'N' & 'L'	'P'	'S1'	'S2'	'T'	'T'
T _{in} (°F)	637	615	633	635	636	636
P _{in} (psig)	74	75	75	75	76	75
T _{max} (°F)	1659	1659	1846	1783	1933	1960
Φ _{primary}	1.20	1.12	1.27	1.25	1.39	1.37
NO _x (ppm) (lbm/MMBtu)	147 (0.5901)	192 (0.8200)	48.9 (0.2082)	64.4 (0.2686)	49.0 (0.1976)	48.8 (0.1950)
CO (ppm) (lbm/MMBtu)	90.0 (0.220)	15.8 (0.0395)	4.3 (0.011)	6.6 (0.0160)	2.6 (0.0066)	2.2 (0.0050)
SO _x (ppm) (lbm/MMBtu)	165.0 (0.9230)	368 (2.05)	164 (0.958)	170 (0.995)	—	—
ΔP/P Primary (%)	4.0	4.1	4.0	4.0	4.1	4.0
Carbon Conversion	—	94	—	—	—	—
Slag Capture (wt%)	63	37	68.9	54.0	70	—
Heat Input (MMBtu/hr)	4.29	4.32	4.14	4.32	4.70	5.08

*See Appendix A for test fuels data.

temperatures measured in the refractory at a depth of about one-half inch reached a maximum average value of 1811 and 1883° F in Test Nos. 45 and 46, respectively. A thermocouple mounted flush with the inner refractory surface located slightly below the impactor reached a maximum of 1683 and 2040° F, respectively.

Post test inspection revealed that only a small amount (less than one pound for each test) of slag reached the water bath. The water flush carried approximately half of this slag into the lock hopper. Most of the slag froze only several inches below the impactor well above the slag tap hole. The slag tap hole was virtually clean. The results indicate that the slag tap was too cool for both tests. In TSSC Test No. 46 an effort was made to reduce the heat transfer from the slag tap area. This design modification was slightly successful as indicated by the temperatures cited above, but still the slag tap was too cool. These tests indicated that more work was required in efficiently heating the slag tap.

In order to decrease heat loss from the slag tap a series of insulation geometry tests were completed at atmospheric pressure running the torches only. The slag tap geometries tested are shown schematically in Figure 6a to 6e. This hardware was operated firing the slag tap torches and allowing the exhaust to vent directly into the test cell. The hardware consisted of the impactor spool, the slag tap heating spool, a spacer spool, and the water bath/discharge pipe section. Design Nos. 1 and 2, illustrated in Figures 6b and c, were operated in the CWM combustion tests TSSC Nos. 45 and 46, respectively. Listed in Table 2 are the results of the atmospheric tests with these four slag tap heating geometries. All four designs were tested at the same conditions with gas inlet pressures of 30 psig and air inlet pressures of 4.5 psig. The results clearly indicate that the highest slag tap temperatures are achieved with design #4. "Kaoboard" insulating rings below the slag tap in designs

Figure 5. Baseline TSSC With Water-Quenched Slag Pit

3 and 4 were installed to retard radiant heat transfer from the slag tap to the water bath. These rings had the added benefit of providing an annular gap for torch flame stabilization. In design 4 an insulated spool was added to increase the distance from the slag tap to the water bath. This design more accurately reflects the distance that will be designed into the full scale combustor slag removal system. The design 4 was tested in TSSC Test No. 47 for performance characterization.

In summary, design and test work was completed in the TSSC of a continuous slag removal system. The system consisted of a slag tap, a water bath, and a lock hopper. Initial testing with a 'batch' type water quench slag pit indicated that slag collected in the bath was conveniently sized for handling with a simple lock hopper and additional crushing/augering of the slag would not be required. The presence of a water bath had no noticeable impact on the combustor's performance. Testing with a water bath and lock hopper was started. An isolation valve was opened for slag pit purging successfully in over ten cycles. The purging operation had no noticeable impact on the combustor's operation. Heating the slag tap effectively was important for successful slag removal and work continued in this area.

Figure 6. Slag Test Geometries Tested

Table 2. Slag Tap Heating in Atmospheric Tests Firing Slag Tap Torches Only

	Slag Removal Design Numbers		
	#2	#3	#4
Natural Gas Input (psid)	31.5	31.6	31.5
Torch Air Input (psid)	4.65	4.65	4.65
<u>Temperature*</u>			
Slag Tap (°F)	2050	2345	2432
Refractory Surrounding Tap (°F)	1379	1265	1424
In Gap Between Impactor and Wall (°F)	1021	1168	1136
*Temperatures measured with 15 minutes continuous operation with water in bath.			

The continuous slag removal device development has continued in this reporting period. Preliminary work was completed using a batch water bath and a water bath and lock hopper arrangement. The slag pit geometries tested are included pictorially in Figure 7.

The water flush slag pit was 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 7) with other slag tap geometries tested. The design was 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 was tested in TSSC No. 47. Operating conditions and test results are summarized in Tables 3 and 4. Table 4 also includes data taken in TSSC Tests Nos. 45 and 46 for comparison.

Testing was completed in the TSSC configured as illustrated in Figure 8. This configuration had required that the height of the primary zone be decreased from 24 inches to 16 inches. The height was 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 was 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.

Figure 7. Slag Removal System

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 was attributed to the decrease in primary zone height as described earlier.

This test concluded 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 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.

Table 3. 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	1.36
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 3. Summary of CWM Testing of Fuels of Varying Properties (Continued)

Test No.	53	54	55	56	57	58
CWM (critical property)	"S5" (no additives)	"S8" (fine grind)	"S9" (coarse grind)	"S10" (Upper Freeport)	"S11" (Soldier Creek)	"S12" (Illinois No. 6)
T_n (° F)	624	624	628	654	627	618
P_n (psig)	79.9	78.1	79.7	76.0	77.0	76.0
$\phi_{primary}$	1.297	1.49	1.50	1.44	1.42	1.36
$\Delta P/P$ (%)	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
RESULTS						
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 4. 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

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 was quenched in a water bath after dripping through a slag tap was largely in the form of slag pellets of 0.25 to 0.325 inch diameter. The slag was very brittle and easily crushed by hand. This information indicates that an auger/crusher was not necessary.
- 3) In subscale testing slag tap heating was 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.

PD81179

Figure 8. TSSC Test configuration for Evaluation of Fuels of Varying Properties

3.3 CRUDE OIL EVALUATION

One of the claims for the combustion system being developed on this contract is that it is adaptable to other fuels including crudes and residuals. Tests were performed using the Two-Stage Slagging Combustor (TSSC) and a crude oil from California's San Joaquin Valley to verify the claim. This crude is fairly heavy, therefore if it can be burned satisfactorily, then most other crude oils can be burned.

In order for the crude to flow easily through the delivery piping, barrel heaters were used to heat the fuel prior to the injectors. A typical fuel temperature of 165° F was maintained. Diesel #2 was used as a pilot fuel to heat the rig. The time on pilot fuel was substantially shorter compared to burning CWM, because of the lower ignition temperature for crude. Since it was not necessary to get the primary zone walls up to the usual 2400° F on diesel, as required for CWM ignition, approximately two hours were spent on heating the rig prior to fuel changeover for each test.

In Test 1 the rig was smoothly changed over to crude, and ran for approximately 50 minutes before a leak formed in the primary zone causing a rapid shutdown. Attempting to run a range of fuel flow to characterize the combustor on crude, it was discovered that the fuel delivery system did not respond well at low flows. Several data points were taken with the equivalence ratio ranging, on the rich side, from 1.58 to 1.83. Primary zone temperatures were approximately 2500° F, while transition zone temperatures were around 1900° F. The secondary combustion zone remained unusually cool throughout the test running between 600 to 800° F.

Post-test inspection revealed a melted primary zone. Most of the refractory had flowed down the side walls, at some points exposing the outer steel skin. The refractory settled in the impactor section, although the impactor was still visible and in excellent condition. It appears that some reaction took place between the coal-slag coated refractory and the crude effluent at a critical temperature. Since the impactor was recovered with no damage, it was used for the following test.

Disassembling the rig and looking at the injector section, some degradation of the outer sleeve of one of the injectors was found. Figure 9 shows the injector section after the first crude oil test. Shown in Figure 10 is the injector with a small hole on the side near the weld and the faces of two injectors showing the centered fuel and air assist passage and the build-up around the primary air holes. A new conical piece was fabricated and rewelded to the sleeve. The reason for this rupture is not known but expected to be caused from over-temperature. The remaining injectors were in good condition.

Figure 9. Primary Injector Section After the TSSC Crude Oil Test

(A)

(B)

Figure 10. A) Hole Near Weld on Primary Zone Injector; B) Injector Face

New primary, secondary, and transition zones were fabricated and testing continued. In Test 2, the diesel start was very smooth as was the switch to crude and temperatures quickly increased. The equivalence ratio was varied as much as possible and emission points were taken. Since this was the first test using the effervescent atomizer, the air assist was also varied to observe any effect on combustor performance and emissions.

While varying equivalence ratio, primary zone wall temperatures ranged from 2443 to 2662° F while secondary outlet temperatures ranged from 1417 to 2052° F. In light of extraordinarily high crude oil pump pressures, above the 600 psig maximum of the gauge, rig pressure was decreased to 60 psig in order to continue the test at near design conditions. Emissions data shown in Table 5 were typical, operating in O₂ ranges of 13.2 to 16.4%. Data shown is corrected to 15% oxygen. Figure 11 shows how the NO_x is effected by varying the equivalence ratio and the air assist pressures at the injector. The graph in Figure 12 illustrates how well the combustor performed showing the primary zone equivalence ratio versus the measured oxygen content in the exhaust.

Given the high temperatures and limited fuel and rig pressure ranges, approximately 375 pounds of crude oil was burned. Toward the end of the run, instead of the usual switch over to diesel, diesel was pumped into the holding tank containing the remaining crude oil with the expectation of simultaneously flushig out the fuel system lines and reducing the temperature of the rig. No fuel density nor temperature change was observed, therefore the fuels must have co-mingled in the tank.

Preliminary inspection revealed clean, intact primary zone walls, impactor section, and residence section. However, the face of one injector, which was removed for inspection, was badly burnt, stripping away the primary air weld around the annulus. Also, a relatively large amount of soot was stuck to the fuel port exit. One injector was flowed with water for a visual inspection. The spray was skewed off center and a strong jet steamed the center of the spray. Albeit, good atomization was observed. It is presumed that although primary air escaped from the broken weld, the injectors yielded a fair performance.

Table 5. Emissions Data From TSSC Crude Oil Test 2

All Data Taken at DP/P = 3.8% PPRI = 63 psig						
W Fuel (pph)	Pres AA (psig)	PHI	O ₂ %	NO _x (ppm)	CO (ppm)	UHC (ppm)
152	150	1.35	15.89	124.8	16	7.4
145	150	1.25	15.97	161.8	14.9	7.7
140	150	1.43	16.38	283.6	15.5	8.4
136	150	1.4	16.57	—	15.5	9.4
132	150	1.18	16.72	494.8	15.3	9.7
186	150	1.72	15.09	145.7	11.6	5.7
211	170	1.87	14.05	166.2	8.9	5
218	190	1.94	13.3	172.7	7.3	4.5
228	210	1.92	12.79	—	6.7	4.6
211	214	1.76	13.54	164.4	7.4	4.8
204	210	1.72	13.94	138.8	7.8	5.3
190	212	1.82	14.39	107	9.5	6.4
181	212	1.58	14.53	117.4	8.5	5.4
153	212	1.54	15.4	107.2	10.1	6.2

Figure 11. Effects of Varied Air Assist Pressures on NO_x

Figure 12. Combustor Performance Shown by Primary Zone Equivalence Ratio vs. Measured Oxygen in the Effluent

3.4 SULFUR OXIDE REMOVAL

Sulfur in coal exists as organic sulfur and inorganic sulfur (primarily pyrite FeS_2). The organic sulfur may occur as side-chains to the hydrocarbon ring structure and as thiophene compounds within the ring structure. The latter form appears to be dominant. Upon injection into the primary zone of a coal combustor the coal particles undergo devolatilization to aromatic, aliphatic, and inorganic sulfur compounds. Thermal and reductive decomposition of pyrite is expected to yield sulfur (S_2), hydrogen-sulfide (H_2S), and carbonyl sulfide (COS). Experiments have shown that organic sulfur also gives a fair yield of light gas; the remainder being sulfur condensibles. Hydrogen sulfide appears to be an important light gas from coal devolatilization. The combustion literature abounds with studies on sulfurous flames and reactors. However information on the concentration and chemical kinetics of fuel-sulfur in hydrocarbon combustion systems is incomplete. The gas-phase composition about coal particles is predominantly a mix of hydrocarbon and air. The fuel-air equivalence ratio varies from fuel-rich near the coal particle to possibly fuel-lean in the main gas stream. In addition, sulfur release from coal devolatilization can be inhibited by inherent capture of coal-bound mineral matter, particularly calcium oxides and sodium oxides:

which in the slagging combustor design may be removed with the slag. Thus, the fate of the fuel-sulfur in this zone is not well understood.

In a staged combustion system where the primary zone is fuel-rich to minimize the formation of NO from fuel-bound nitrogen, the sulfur species produced during the various reactions are predominantly H_2S , COS , and carbon disulfide (CS_2). These compounds are, however, quickly oxidized in the lean secondary to sulfur dioxide and a smaller amount of sulfur trioxide which is then emitted in the exhaust.

The oxides of sulfur resulting from direct coal-fired combustion can be reduced by three different processes:

- (1) Sulfur removal from the coal prior to combustion
- (2) Sulfur removal during the combustion process by sorbent materials
- (3) Exhaust scrubbing systems.

Physical cleaning of coal can be very effective in removing inorganic sulfur, especially pyrite. However, to achieve sulfur levels in the coal to meet anticipated sulfur emission requirements, a combination of physical and chemical coal cleaning is required, and these processes are very costly.

Exhaust scrubbing systems are being used in the coal-fired utilities but are also expensive due to the large scale of the necessary components.

Work done exploring the use of dry calcium-based sorbents in coal-fired utility boilers indicate that significant reductions in SO_x can be achieved. Gas turbine combustion differs from utility boiler combustion in two ways: (1) residence times in the gas turbine combustor are much smaller and, (2) pressures are much higher. Shorter residence times are a disadvantage for SO_x absorption while increased pressure helps promote a Ca-S reaction.

Richard Newby of Westinghouse R&D was retained to consult on the desulfurization of Solar's coal-fired combustor exhaust stream. Discussions were held in six different areas: sorbent injection location, sorbent type, kinetic modeling evaluation, measurement techniques, sulfur removal influence on the total system, and integrated sulfur removal with particulate control.

The secondary zone, injecting with secondary air, is the probable best location for sorbent injection for the Solar test work. It may be found that excessive sintering occurs at this location, in which case injection downstream of the secondary zone will be preferred. While the Solar test unit will have limited particle residence time downstream of the secondary zone, and high efficiency removal may not be possible in the test unit, commercial designs may use high-temperature filters that add considerable residence time and make the down-stream injection even more effective. The primary zone injection is complex and should only be attempted if a major development effort can be established. A fluidized bed desulfurizer stage following the secondary zone is an attractive backup to fine sorbent injection.

The overall choice of sorbent was, in reality, site and fuel specific to some extent. For the Solar testing the following sorbents are recommended: (1) Lime hydrate, (2) Hydrated dolomite (atmospheric or pressurized), and (3) Dolomite.

The approximate relative cost of these materials (relative to the cost of bulk limestone of a coarse, normal quarry size) per ton delivered is:

- limestone or dolomite sized to -325 mesh = 1.5 to 2
- commercial limes or calcined dolomites = 3
- lime hydrates or monohydrated dolomites = 4
- dehydrated dolomites = 5
- activated limes = 10

Additives to improve sorbent performance are currently being tested in atmospheric pressure systems. Performance improvements are not great, and such additives may introduce corrosive species into the turbine. Their use was not recommended.

Alternative sorbent materials can be identified that have the thermodynamic potential to remove sulfur in the Solar combustor. They are all at least an order-of-magnitude more expensive than calcium-based sorbents and required the use of complex sorbent regeneration processes to be economical. They should be considered only if calcium-based sorbents fail to be effective.

Calcium-based sorbents will not capture sodium or potassium released from coal in the combustor. In fact, the sorbents will generally be a source of alkali. The sodium contents of limestones and dolomites range from 0 to 2000 ppm, with most of it being in a soluble form. The potassium contents of limestones and processed sorbents (limes and hydrates) may be lower, but little data exist on this.

Sorbent injection into the slagging zone obviously has a great impact on the nature of the slagging phenomena and the properties of the slag formed. The T250 temperature is a common measure of the slag properties, and general criteria relating it to the sorbent feedrate have been proposed in the literature.

Measurements of SO₂ reduction in the exhaust gases of the subscale two-stage slagging combustor through injection of calcium-based sorbents were made. An extension piece was added above the secondary zone of the TSSC as illustrated in Figure 13 to increase available reaction times between the calcium-based sorbents and SO₂ laden exhaust gases. Measurements of SO₂ concentration

Figure 13. Sorbent Injection Experimental Test Set-up

were made at the exit of the secondary zone and at the exit of the residence time test section. Sorbent was injected in the secondary zone with the incoming secondary air at only one port.

Sorbent was delivered via a dense-phase pneumatic sorbent feed system consisting of a delivery tube and feed tank. The feed tank is illustrated in Figure 14. Sorbent was conveyed up the delivery tube with a carrier gas (heated nitrogen) at mass ratios of 5-10 to 1 sorbent to carrier gas. This system and its operation have been described in detail elsewhere (Ref. 1).

Testing of the subscale coal-fueled combustor was aimed at evaluating sulfur removal effectiveness of powdered dolomite injection into the secondary zone. Sulfur dioxide reductions as high as 90% have been measured. SO_2 reduction versus Ca/S molar ratio is shown in Figure 15 for Tests Nos. 5 and 8. These tests were run at 80 psig and 620° F inlet air. Fuels Amax 'C' and Amax 'D' were burned in Test 5 and 8, respectively. Sulfur dioxide reductions are based on the theoretical maximum SO_2 level calculated from the measured fuel/air ratio and sulfur content of the parent coal. Figure 15 indicates that at Ca/S ratios above 5.0, more than 80% SO_2 reductions can be achieved. All SO_2 measurements were taken at the exit of the extension piece on the secondary zone allowing approximately 200 msec residence time for the sorbent particles to react with the exhaust gases.

Figure 14. Dense-Phase Pneumatic Sorbent Feed Tank

Figure 15. SO₂ Reductions for Dolomite Injected in the Secondary Zone

Actual emissions data from these tests are included in Figure 16. These data are taken at the exit of the residence time test section. SO₂ emissions without sorbent injection vary with coal sulfur level as indicated in this figure. Comparison between measured and calculated SO₂ emissions show excellent agreement with Ca/S molar ratios greater than 5.0, SO₂ emissions can be reduced to less than 40 ppm @ 15% O₂ with a 0.9 sulfur wt% fuel and to below 10 ppm @ 15% O₂ with a 0.56 sulfur wt%.

Particulate sample collected during Test No. 5 was analyzed. The chemical analysis of the solid material and dilution water is included in Table 6. The sample was taken while injecting dolomite at a Ca/S molar ratio of 5.5. The particulate analysis indicates little increase in sulfur concentration. Analysis of the dilution water shows a marked increase of sulfur in solution. The ash and dolomite analysis of the particulate are a combination of ash and spent sorbent.

SEM photographs of the raw dolomite and the spent sorbent and ash are included in Figures 17 and 18, respectively. The raw dolomite sample was a homogeneous crystalline structure with little visible porosity. SEM analysis, shown in Figure 17B, indicates the structure was largely calcium and magnesium. The spent sorbent and ash particulate pictured in Figure 18A was non-homogeneous, and three separate materials can be identified. The particulate was primarily large (greater than 10 microns), amorphous, slightly porous, unspent sorbent particles covered with small nodules of spent sorbent and flyash. SEM analyses of both the large particles and smaller nodules are shown in Figures 18B and 18C. Figure 20B indicates little if any sulfur present, while Figure 18C indicates measurable quantities of sulfur and the constituents of coal ash (Al, Si, Fe, etc.). The third substance observed in the particulate is not pictured, but a SEM analysis of it is included in Figure 19. The material was spheroidal and regular with a smooth "glassy" surface. The analysis indicates

Figure 16. Actual Measured SO₂ Levels at Varying Dolomite Injection Rates Compared to Theoretical SO₂ Levels Based on Fuel Sulfur Content With No Sorbent Injection

it was a frozen slag droplet and its image supports this interpretation. Difficulty in analyzing the particulate for sulfur species results from the water-quench sampling technique which tends to put the sulfur in solution removing most sulfur from the particulate. A sample gathered without water dilution was necessary to validate some of these conclusions.

In order to resume sorbent evaluation testing two steps had to have been taken to obtain SO₂ reduction data at Ca/S ratios less than 5. First a CWM made from a coal with a sulfur concentration of 1.4 wt% was ordered. By doubling the coal sulfur concentration the required sorbent feed rates were increased. To maintain a Ca/S ratio of 3 the feed rate was increased from 39 to 73 pph, a flow rate which was demonstrated by the dense phase pneumatic feed system.

The second step to obtain data was construction of an auger-type screw feeder, as illustrated in Figure 20. The screw feeder was designed, manufactured, and delivered. Shakedown tests to determine sorbent flow rate as a function of auger speed have been completed. Figure 21 shows the relation of sorbent flow rate with auger speed and dial setting. As is evident both of these are linearly related to sorbent flow rate at atmospheric pressure. The sorbent flow rate was also measured through the weight difference of the sorbent tank over a known time interval. The agreement of measuring sorbent flow rate by tank weight difference and dial setting (collected sorbent weight) was within 2%. The auger continues to demonstrate a linear relation between dial setting and feedrate at combustor pressures as determined by comparing flow rates measured by tank weight difference and dial settings. The linear relation holds true up to a flow rate of 100 pph.

Table 6. Particulate Analysis of Sample Collected in Test No. 500 With Dolomite Injection

Fuel: AMAX 'C'	
Dolomite: National Minerals Dolowhite #100 Select	
Ca/S 5.5	
<u>Particulate (wt%)</u>	
Carbon	39.2
Sulfur	0.62
Ash and Dolomite	60.18
Ash	40.09
Spent Sorbent	59.90
<u>Ash and Dolomite (wt%)</u>	
CaO	45.9
MgO	27.1
SiO ₂	14.75
Al ₂ O ₃	4.25
Fe ₂ O ₃	4.12
Na ₂ O	1.64
TiO ₂	0.30
K ₂ O	0.25
MnO ₂	0.11
<u>Dilution Water (ppm)</u>	
SO ₄	620.0
Ca	191.3
Cl	124.0
Na	114.0
K	7.2
Si	3.3
Li	0.1

(A) Before Injection

(B) SEM Analysis

Figure 17. Raw Powdered Dolomite

(A) Sorbent/Ash Particulate

**(B) SEM Analysis of Smaller Nodules
Located on Particles**

**(C) SEM Analysis of Larger Particle
Surface of Sample**

Figure 18. Sorbent/Ash Particulate Collected in Test No. 5

Figure 19. SEM Analysis of "Glassy" Spheroid in Particle Sample

Figure 20. Sorbent Screw Feeder

Figure 21. Sorbent Screw Feeder Atmospheric Calibration

The TSSC was run to evaluate dolomite, pressure hydrated dolomitic lime (PHDL, $\text{Ca}(\text{OH})_2\text{Mg}(\text{OH})_2$), and hydrated lime (HL, $\text{Ca}(\text{OH})_2$). The sulfur capture of both PHDL and HL was superior to dolomite with HL slightly better than PHDL. HL has demonstrated SO_2 reductions as high as 90 at Ca/S ratio of 3.0 burning CWM 'O' (1.4 wt% S). The difference between sorbent effectiveness of HL and PHDL was only slight and selection of one of these sorbents was appropriate from a sulfur removal standpoint. It should be remembered that other factors such as cost, and the ability for the secondary filter to handle each sorbent must be considered when rating the sorbent types. The sorbent test plan still calls for evaluation of limestone ground with the CWM and delivered in the primary zone.

The properties of all the sorbents are included in Tables 7 and 8. These analyses were provided by the supplier and AMAX R&D, respectively. As is evident from the tables all three sorbents are composed primarily of calcium and magnesium compounds with ash concentrations for dolomite, PHDL, and HL of 0.67%, 0.60% and 0.60%, respectively. Dolomite has a much higher bulk density and a slightly higher true density than the other sorbents. The sieve analysis indicates that HL, PHDL, and dolomite, respectively, have slightly increasing particulate size. The median particle sizes shown in Table 8 confirm this characterization. Also shown in Table 8 is the specific surface area and porosity of all three sorbents. As indicated dolomite has a much lower surface area and is less porous than the other two sorbents. All three are commercially available sorbents typical of those expected to be used in the CFC.

Table 7. Chemical and Physical Analyses of Calcium-Based Sorbents Used in Recent Tests

	<u>Dolomite</u>	<u>PHDL</u>	<u>HL</u>
Supplier Brand Name	National Minerals Dolomite #100	ChemStar Type S Hydrided Lime	Chemstar High Calcium Hydrated Lime
Bulk			
Density (lbs/ft ³)	60	25	86
Specific gravity	2.86	2.24	2.23
Cost (\$/ton)	20.00	119.00	119.00
<u>Chemical Analysis</u>			
Acid Insoluble	--	0.40	1.5
Fe ₂ O ₃	0.12	0.10	0.10
SiO ₂	0.47	--	--
Al ₂ O ₃	0.08	0.50	0.50
MgCO ₃	42.57	--	--
CaCO ₃	57.20	1.50	1.50
CaO	--	--	Trace
MgO	--	0.60	1.00
Mg(OH) ₂	--	40.00	--
Ca(OH) ₂	--	55.00	95.00
H ₂ O	0.1	0.4	0.50
ASTM Lime % Available	--	--	
<u>Sieve Analysis</u>			
(% Less) (microns)			
297	99.3	99.0	100
149	90.0	96.0	100
105	76.0	90.0	99
74	57.0	86.0	97
44	40	79.0	88
30	35.0	--	--
20	27.0	--	--
10	15.0	--	--
5	9.0	--	--
2	3.0	--	--
1	7.0	--	--
Surface Area (M ² /gm)	--	25-30	20-30

Table 8. Analyses of Calcium-Based Sorbents

Supplier Brand Name	<u>HL</u> ChemStar High Calcium Hydrated Lime	<u>PHDL</u> ChemStar Type S Hydrated Lime	<u>Dolomite</u> National Minerals Dolomite #100
Loss on Ignition Weight %	24.2	26.9	46.2
CO ₂ , Weight %	0.62	0.95	44.3
SO ₃ , Weight %	0.007	0.005	0.042
Hydration H ₂ O (Diff.) Weight %	23.6	25.9	1.9
Dry Sieve, Weight %			
-150 µm	99.1	88.1 ⁽¹⁾	87.4 ⁽²⁾
-75 µm	97.3	27.1 ⁽¹⁾	65.7 ⁽²⁾
-45 µm	92.7	15.2 ⁽¹⁾	53.1 ⁽²⁾
Specific Surface, m ² /g	18.7	20.1	0.51
Mercury Porosimetry			
Particle Density	1.88	1.98	2.64
Bulk Density	1.49	1.52	0.62
Internal Porosity, cc/g	0.61	0.65	small ⁽³⁾
Median Pore Size (µm) (50% relative pore volume)	0.58	0.22	4.5 ⁽⁴⁾
⁽¹⁾ Hard lumps, previous test on Type S lime gave 92.7% minimum 45 µm. ⁽²⁾ By wet sieving. ⁽³⁾ Pore volume versus pore diameter data difficult to interpret. ⁽⁴⁾ Including the interstitial space size between particles.			

Listed in Table 9 are the test conditions and combustor performance results of test Nos. 30, 31, and 32 in which the three sorbents were evaluated. Test conditions were typical of previous testing to evaluate other aspects of combustor performance with air inlet temperatures of 620°F and combustor pressure of 80 psig. Outlet temperatures are maintained between 1730° and 1790° F in all testing. Tests were conducted in the baseline combustor with conical primary zone walls. The fuel injectors have modified air/assist and fuel tip assemblies that have shown in atomization studies to produce CWM droplets of SMD 30 microns. The test fuel was CWM 'O' which has the same characteristics of all recent test fuels (54% coal, 45 micron top-size, 300 cp viscosity, and 4% ash) with the exception of a sulfur wt% of 1.4. At a primary zone equivalence ratio of 1.3, this CWM could generate a maximum SO₂ concentration in the exhaust of 280 ppmvd @ 15% O₂.

Table 9. Result of Combustor Performance with Three Sorbents Injected Into Secondary Zone

	Sorbent Injected		
	Dolomite	PHDL ⁽¹⁾	HL ⁽²⁾
Test No.	29	31	32
Fuel ⁽³⁾	'O'	'O'	'O'
T _{in} (° F)	616	628	637
P _{in} (psig)	75	74.9	73.6
Φ _{primary}	1.19	1.27	1.42
T _{outlet} (° F)	1731	1738	1786
Results			
Emissions @ 15% O ₂			
NO _x ppmv (lbm/MMBtu)	117 (0.9738)	92.3 (0.3735)	78.9 (0.3145)
CO ppmv (lbm/MMBtu) (no sorbent)	9.19 (0.0226)	7.34 (0.0179)	15.88 (0.323)
Carbon Conversion %	99.8	98.9	97.6
Sorbent Injection Range (pph) (Ca/S)	24-145 (0.94-5.7)	6-46 (0.55-4.10)	14-36 (1.15-2.91)
SO ₂ Reductions (%) @ Ca/S of 3.0	55	82	90
Ca/S @ SO ₂ - 75 ppmv	3.4	2.4	1.5
⁽¹⁾ Pressure Hydrated Dolomitic Lime ⁽²⁾ Hydrated Lime ⁽³⁾ See Appendix A for fuel data			

Pollutant emissions shown in Table 9 are characteristic of tests with the conical primary walls and modified injector. NO_x emissions are well below goal of 125 ppmvd and CO emissions are well below 50 ppmvd with the standard relation with equivalence ratio shown. The carbon conversion is seen to vary from 97.6 to 99.8% dependent on the equivalence ratio with a value of 99% close to design setting.

Sorbent results are summarized in Table 9 and included in greater detail in Figures 22, 23, and 24. Figure 22 indicates the SO₂ emissions reductions resulting from dolomite injection as a function of molar Ca/S ratio. SO₂ reductions are calculated as the measured SO₂ with sorbent injection that quantity divided by the measured SO₂ without sorbent injection. All SO₂ emissions samples are

Figure 22. SO₂ Emission Reductions for Dolomite Injection in the Secondary Zone

Figure 23. Comparison of SO₂ Reduction for Three Calcium Sorbents Injected into the Secondary Zone of the TSSC Burning a CWM with 1.4 wt% Sulfur

Figure 24. Comparison of SO₂ With Varying Injection Rates of Three Sorbents Into the Secondary Zone of the TSSC

drawn continuously from the outlet of the residence time test section, which was a refractory lined pipe mounted on top of the secondary zone providing an additional 150 ms of exhaust gas residence time at 1850°F before water quench addition. Sulfur dioxide concentrations are measured with a Western Research UV SO₂ Gas Analyzer. Measured SO₂ emissions are compared with theoretical SO₂ emissions assuming all the sulfur in the CWM was converted to SO₂ at the exhaust. Typically the theoretically-calculated SO₂ levels are 10 to 15% higher than the measured SO₂ emissions without sorbent injection.

In Figure 23 the same dolomite curve is shown with SO₂ emissions reduction data taken injecting PHDL and HL into the secondary zone. As summarized in Table 9 at a Ca/S ratio of 3, which was the design sorbent loading, reductions of 55, 82, and 90% are achieved with dolomite, PHDL, and HL, respectively. The sorbent injection ranges listed in Table 9 are the required mass flows to vary the Ca/s ratios over an anticipated operation range. The Ca/S ranges are also listed. The measured exhaust SO₂ concentrations for these tests are included in Figure 24. As shown in Figure 24, SO₂ concentration drops off fastest with Ca/S ratio while injecting HL. It should be remembered as indicated in Table 7 that the particulate size of the three sorbents vary as noted with dolomite being the largest grind and hydrated lime the smallest grind. This trend suggests that the sulfur capture results of the three sorbents may also be partially attributed to particle size. No effort was made to separate the two factors that vary in this study of sorbent particle size and chemical composition at the present time. The sorbent samples were selected from commercial sources because they represent the stock that would be used in the CFC. However, in view of the results, the independent influence of particle size and sorbent chemistry on sulfur capture requires further study. To achieve Solar's design SO₂ emissions goal of 75 ppmvd while burning CWM 'O'; HL, PHDL, and dolomite must be injected at Ca/S ratios of 1.5, 2.4, and 3.4, respectively.

The performance of dolomite relative to PHDL and HL was anticipated and had been documented in past work. The performance difference between PHDL and HL was only slightly above measurement error, but does indicate that HL was superior. Richard Newby of Westinghouse R&D consulting to Solar accurately assessed the relative effectiveness of these three sorbents in the TSSC including the slight improvement of HL over PHDL. The costs of dolomite, PHDL, and HL are shown in Table 7. The table indicates that HL and PHDL have comparable costs while dolomite is about one-sixth of the others. PHDL was the least favorable candidate sorbent for use in the CFC based on the cost, sorbent effectiveness, and material handling. Dolomite was favored for sorbent injection based on cost and material handling, but for high sulfur CWM's would require quantities well in excess of Ca/S of 3. The effectiveness of dolomite should improve with the secondary filter installed due to the added residence time it will provide. A final sorbent selection can not be made until tests are conducted with the secondary filter. Tests are still planned to inject limestone mixed with the CWM into the primary zone.

The sorbent evaluation test plan was completed with several more subscale tests in the TSSC. The test set-up and procedure was described in detail in LeCren et.al., 1989 and Cowell et.al., 1990. Recent work has focused on sulfur capture with high sulfur CWM, with sorbent mixed with the slurry, and sorbent injection of finer grinds. Test conditions and results are summarized in Table 1 under TSSC Test Nos. 34, 35, 36, and 42.

Two tests (Nos. 34 and 35) have been run using CWM 'F' as the fuel. The properties of CWM 'F' and 'G' are shown in the Appendix. Both CWM 'F' and 'G' are made from the same source coal which contains a higher sulfur loading (3.13 versus 1.0 wt% sulfur) than was used in most testing. The principle difference between CWM 'F' and 'G' is that 'G' was made with pressure hydrated dolomitic lime (PHDL) ground with the coal during CWM preparation. Several other properties that differ substantially between 'F' and 'G' are the coal content, ash content, and carbon content. The purpose of testing with CWM 'F' was two-fold: first, to establish a set of SO₂ baseline data without any sorbent addition including collecting and analyzing slag samples; and secondly, to evaluate dolomite for sulfur capture at higher SO₂ concentrations.

The data taken while burning CWM 'F' is graphically summarized in Figures 25 and 26. Figure 25 shows the SO₂ reductions at varying Ca/S ratios for dolomite injection burning CWM 'F' and other CWMs (sulfur loadings of 0.56 to 1.44 wt%). Sulfur dioxide reduction was calculated as the measured SO₂ without sorbent injection minus the measured SO₂ without sorbent injection. This data indicates that a slight increase in sorbent effectiveness was realized as coal sulfur loading was increased. The result had been predicted by Newby (Westinghouse R&D consulting to Solar) and others. The effect wasn't noticeable as the coal sulfur level was varied from 0.56 to 1.44 wt% because the experimental error was relatively large compared to the improved gains in sulfur capture. Absolute SO₂ concentrations are included in Figure 26 and coincide with the data presented in Figure 20. In summary the dolomite effectiveness at a Ca/S ratio of 3.0 was 63% reduction in the SO₂ level. This reduction still leaves an SO₂ concentration of 200 ppmv which was well above the 75 ppmv goal of the CFC. In order to reduce SO₂ concentrations to 75 ppmv injecting dolomite at a Ca/S ratio of 5.5 to 6.5 (extrapolating from Figure 26) would be required.

One test (Nos. 36) was performed using CWM 'G' as the fuel. The purpose of testing with CWM 'G' was to evaluate the sulfur capture effectiveness of grinding a sorbent with the coal during slurry preparation and injecting the slurry in the primary zone as a sorbent-coal fuel. By combining the CWM and sorbent delivery a substantial savings to the system cost could be realized.

Figure 25. SO₂ Reduction of Dolomite Injected in the Secondary Zone of the TSSC Burning CWMs of Varying Sulfur Loading

Figure 26. SO₂ Emissions at Varying Ca/S Ratios of Dolomite Injection

In TSSC No. 36 the SO₂ emissions are not noticeably lowered by the sorbent mixed in with the fuel. Comparing the SO₂ emissions measured without sorbent injection from Test No. 35 (658 ppmv) with these results from Test No. 36 (648.7 ppmv), the SO₂ reduction was less than 2%. The reduction based on theoretical emissions was 12.8%. These reductions do not compare favorably to earlier results taken injecting sorbents into the secondary combustion zone. Analysis of slag collected from the slag pit indicates that only 0.4% of the coal sulfur was removed with the slag. This result supports that sulfur capture by the calcia in the primary zone was poor. Another serious consequence of mixing the sorbent with the CWM was that calcium reacts with the alumino-silicate refractory walls under reducing conditions to create a eutectic with a lower melting point. During testing severe erosion/melting of the walls took place.

The final area to be investigated was the impact of sorbent grind size on sulfur capture. During TSSC Test No. 42 dolomite of a finer grind was injected into the secondary zone through one of the secondary air inlet lines using the sorbent auger feed system. The dolomite was procured from National Minerals as were previously tested samples. The only difference between this supply and past supplies was the dolomite mesh. Past batches of dolomite were a 50 mesh size which corresponds to an approximate 300 micron top-size. This batch was 325 mesh with a corresponding top-size of 45 microns. Properties of these dolomites are included in Table 10.

The results of testing with this sorbent compared to dolomite tested previously with a larger particulate size are shown graphically in Figure 27. In this figure, SO₂ reduction is plotted against Ca/S molar ratio for both grinds of dolomite. The finer grind of dolomite improves the sulfur capture as expected. The degree of improvement was less than anticipated. Richard Newby of Westinghouse R&D while consulting for Solar predicted that approximately halving the dolomite particle size should double the sulfur reductions. In this test work reducing the particle top size from 300 to 45 microns has led to only a 30% improvement in SO₂ reductions. The results suggest that using finely ground dolomite offers only a slight advantage over coarse grinds in terms of SO₂ reductions.

In summary, recent testing evaluating sorbents for sulfur capture have indicated that a slight improvement in sorbent sulfur removal efficiency was realized with increased sulfur loading of the CWM. Sorbent ground with CWM and injected into the primary combustion zone as a fuel/sorbent does not demonstrate high SO₂ reductions. Particle size of the sorbent does have a strong influence on sulfur capture, however not as strong an influence as predicted by others.

3.5 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 were completed with fuels formulated with a range of properties. The purpose of the testing was to determine the limits for the fuel specification needed 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 were completed in the TSSC configuration with the water quench slag removal system as illustrated in Figure 28.

A listing of all the fuels used and their properties are included in Table 11. The tests completed with these fuels and the important results are summarized in Table 12.

Table 10. Properties of Dolomite of Different Grinds

	Dolomite D-303	Dolomite D100
Composition, %		
SiO ₂	0.85	0.47
Al ₂ O ₃	0.05	0.08
TiO ₂	<0.01	—
Fe ₂ O ₃	0.12	0.12
CaO	29.80	29.7
MgO	18.90	22.4
SrO	<0.01	—
Na ₂ O	<0.001	<0.001
K ₂ O	<0.001	0.002
P ₂ O ₅	0.08	—
MnO ₂	0.03	—
PbO	<0.01	—
Cr ₂ O ₃	<0.01	—
NiO	<0.01	—
V ₂ O ₅	<0.01	—
SO ₃	0.001	—
CO ₂	47.1	47.9
Loss on Ignition	46.6	—
Insoluble in Acid	1.13	—
Specific Surface, m ² /gram	1.01	0.51
Mass Mean Diameter, μm	18.1	
Particle Size Distribution, Weight Passing, %		
297 μm		99.3
150 μm	99.9	90.0
75 μm	99.9	57.0
53 μm	97.7	40.0
45 μm	87.9	—
38 μm	88.1	35.0
30 μm	84.1	27.0
20 μm	68.5	—
15 μm	56.2	15.0
10 μm	40.3	—
8 μm	33.9	—
6 μm	27.4	9.0
4 μm	20.3	—
2 μm	9.2	3.0
1 μm	0.7	1.0
X-Ray Diffraction		
Dolomite	Predominant	Predominant
Calcite	Trace	Trace
Anhydrite	None Detected	None
Sodium Sulfate Phases	None Detected	Detected
		None Detected

Figure 27. Comparison of SO₂ Reductions of Dolomite of Varying Sizes Injected into the Secondary Zone

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Figure 28. TSSC Test Configuration for Evaluation of Fuels of Varying Properties

Table 11. Properties and Compositions of Combustion Testing Fuels

CWM TSSC Test No.	S-1 48	S-2 44	S-3 49	S-4 50	S-5 53	S-6 51	S-7 52	S-8 54	S-9 55	S-10 56	S-11 57	S-12 58
Coal Source	----- Kentucky 4A/Eldhom -----									Upper Freeport	Soldier Creek	Illinois No. 6
Moisture Content (wt%)	45.56	45.27	41.34	49.61	56.56	45.71	45.65	45.48	45.77	46.22	45.68	45.89
Coal Content (wt%)	53.88	54.20	58.17	49.95	43.44	53.60	53.60	53.77	53.75	53.05	53.74	53.50
Ash Content (wt%)	2.05	2.06	2.33	2.03	1.72	4.80	6.98	2.10	2.13	5.86	2.78	3.47
A-23 (wt% of coal)	0.875	0.845	1.525	0.69	0.00	1.27	1.30	1.35	0.89	1.37	1.10	1.10
Flocc (wt% of coal)	0.04	None	0.016	0.015	0.00	0.005	0.02	0.02	0.01	None	0.01	0.005
Particle Size												
% Passing 100 micron	100.00	100.00	99.90	99.94	99.41	99.99	100.00	99.99	99.90	-	99.89	99.94
% Passing 75 micron	99.88	99.88	99.67	99.89	98.67	99.85	99.85	99.85	99.43	99.85	99.87	99.59
% Passing 45 micron	98.75	98.76	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	96.65	97.76	93.49	98.22	98.42	99.44	94.28	98.66	98.50	98.11
% Passing 30 micron	93.84	93.84	91.09	94.21	87.84	96.09	96.40	99.22	90.35	96.42	94.79	95.31
% Passing 20 micron	85.35	85.35	82.18	87.94	78.89	90.81	91.28	93.15	71.63	90.83	85.88	81.28
% Passing 15 micron	75.61	75.61	69.30	73.18	65.77	83.20	81.63	86.46	59.87	87.01	74.69	63.64
% Passing 10 micron	58.51	58.51	52.50	58.13	48.29	68.75	64.48	74.67	41.57	73.44	56.03	46.60
% Passing 8 micron	51.04	51.04	45.49	47.44	39.83	55.98	55.53	67.81	34.29	65.01	48.23	38.41
% Passing 6 micron	43.32	43.32	39.45	38.60	31.17	46.46	46.28	56.39	28.11	54.56	39.58	30.97
% Passing 4 micron	33.73	33.73	28.01	25.78	20.83	35.47	34.78	41.84	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	18.67	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	4.96	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	260
@ 1000/sec	280	280	500	185	110	270	300	330	280	115	310	380
Slurry LHV (Btu/lb)	7148	7192	7712	6481	5452	6657	6267	7082	7049	6702	6729	6565
Coal Characteristics												
Proximate Analysis (wt%)												
Ash	3.77	3.77	3.98	4.03	3.96	8.84	12.81	3.85	3.93	10.89	5.14	6.48
Volatiles	35.29	35.29	35.53	35.19	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	76.40	72.51	80.48	80.58	87.53	80.81	80.21
Oxygen	11.50	11.51	11.56	11.83	11.09	15.85	20.31	11.77	11.86	4.34	11.79	10.06
Hydrogen	5.31	5.31	5.34	5.33	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	0.67	2.61
Ash Composition (wt%)												
SiO ₂	46.58	46.58	48.31	47.10	48.83	53.59	56.74	46.85	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	7.67	20.08
CaO	3.99	3.99	3.92	4.88	3.88	2.78	2.12	4.29	4.08	6.13	8.72	1.89
MgO	0.50	0.50	0.50	0.71	0.54	0.63	0.56	1.10	1.64	0.95	1.86	0.38
Na ₂ O	1.29	1.29	1.10	1.25	1.11	0.73	0.56	1.12	1.16	0.26	1.35	0.45
K ₂ O	1.01	1.01	0.92	0.89	0.90	1.40	1.49	0.95	0.82	2.34	0.59	2.72
TiO ₂	1.08	1.08	1.12	1.08	1.08	1.07	1.14	1.07	0.90	1.15	0.59	0.98
P ₂ O ₅	0.16	0.16	0.22	0.19	0.20	0.25	0.17	0.23	0.17	0.01	0.16	0.18
SO ₃	3.11	3.11	3.06	3.59	4.29	1.60	1.93	3.57	4.41	5.80	8.71	1.17
Ash Fusion Temp. (°F)	Oxidizing/Reducing											
Initial Deformation	2659/2310	2659/2310	2440/2254	2445/2381	2372/2311	NA/2179	NA/2069	2479	2369	2409/2304	2255/2132	2467/2057
Softening	2689/2375	2689/2375	2574/2435	2586/2425	2586/2438	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	2553/2155
Fluid	+2700/2687	+2700/2687	+2700/2672	+2700/2631	+2700/+2700	NA/2582	NA/2520	2577	2671	2639/2585	2415/2399	2584/2439

Table 12. 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	1.36
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 (%) (lbs)	-30.1 -5.8	49.3 10.0	17.4 4.63	49.3 24.2	39.1 39.4

Table 12. Summary of CWM Testing of Fuels of Varying Properties (Continued)

Test No.	53	54	55	56	57	58
CWM (critical property)	"S5" (no additives)	"S8" (fine grind)	"S9" (coarse grind)	"S10" (Upper Freeport)	"S11" (Soldier Creek)	"S12" (Illinois No. 6)
T _n (° F)	624	624	628	654	627	618
P _n (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
RESULTS						
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

Analyses of particulate samples were completed to provide the carbon conversion and particulate emissions data included in Table 13. This data were taken with the isokinetic sampling probe. The sample was drawn for a four minute period. The sample was 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 eleven tests are included in Table 13.

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 11. The table illustrates that while slight variations in fuel property

Table 13. Particulate Sample Analyses From Tests 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
<u>Ash Analysis (%)</u>							
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	0.08	0.07
ZnO	0.09	0.10	0.02	2.01	0.09	0.11	0.34
<u>Water Analysis (ppmm)</u>							
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	0.66	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 13. 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
Ash Analysis (%)				
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
Water Analysis (ppmm)				
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

exist the largest variation of the CWM's was in coal loading. Coal loading influences several of the parameters listed in Table 11 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 11 have the same viscosity of 300cp at 100 sec⁻¹, but at 1000 sec⁻¹ vary from 185 to 500cp.

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 12. 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 12 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 was tracked and controlled during testing through the measured air and fuel inputs. The primary equivalence ratio was then calculated based on the measured O₂ concentration. Often a considerable discrepancy can exist between these two for the reasons sighted above.

The outlet temperature was dependent on the primary equivalence ratio and the coal loading of the fuel. This relation is illustrated in Figure 29. 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 was not large for the data taken with fuels of 50 and 54% coal loading.

The emissions are summarized in Table 12 and in Figure 30. The values in Table 12 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 was converted to SO₂. Therefore, neither CO or SO₂ 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 30 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 was increased to a peak at 1.05. As the equivalence ratio was further increased the NO_x emissions fall off rapidly

Figure 29. Outlet Temperature Profile of TSSC Burning CWMs of Varying Coal Loadings

Figure 30. 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 30 illustrate this trend. The figure suggests that the highest NO_x emissions correspond to the lowest coal loading. This was not an expected result. Typically, as the water loading in the combustor was increased the flame temperature was 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 was increased (and water loading was 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 was 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 were uncorrected for equivalence ratio which presents a problem in comparing the results. This was 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 was 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 13 for the three tests. The ash analyses of the particulate usually reflect the ash composition of the coal burned. This trend was not reflected in the data presented in Table 13 in that Fe_2O_3 was the largest constituent for two of the tests (48 and 49) whereas in the coal ash SiO_2 was 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 12 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 12 are substantially lower due to the reduced length of the primary zone. Typically, the primary zone was 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 was $\pm 10\%$ so determining any trend from the data in Table 12 is difficult. The data does suggest that the influence of coal loading on slag capture was not great.

Table 12 also includes the percentage ash emitted. This value was 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 was 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 was

present. The imbalance in the mass balance is included in Table 12 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 was not possible with the data presented.

In summary, three tests were 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 was 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 11. 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 was increased.

The combustor exhibited good operation with all three fuels. The combustor tests were operated at nearly identical conditions as listed in Table 12. Testing was 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 12 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 was 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 12. This trend is further illustrated in Figure 31, which is a plot of outlet temperature versus equivalence ratio for Tests 48, 51, and 52. The outlet temperature was 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.

Figure 31. Variation of Outlet Temperature With Fuels of Varying Coal Ash Concentration

Emissions are summarized in Table 12 and in Figure 32. The values in Table 12 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 was 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 34 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 32 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.

Post-test inspection of the combustor after each of the three tests revealed that as coal ash concentration was 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.

Figure 32. Variation of NO_x Emissions With Fuels of Varying Coal Ash

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 was 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 was 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 13, indicate that the most efficient combustion was completed burning "S7" with the highest coal ash. The carbon conversion was 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 was 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 13 for the three tests. The ash analyses of the particulate usually reflects the ash composition of the coal burned. This trend was reflected in the data presented in Table 13. 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 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 12 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 12 are substantially lower due to the reduced length of the primary zone. The accuracy of the slag capture measurement was $\pm 10\%$ for the low ash coal but improves as the ash concentration was 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 12 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 was obvious when considering an ash mass balance in the system. Ash not captured as slag in the primary zone was 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 12 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 were 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 11. 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 was 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 12. 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 was not supported by the viscosity measurements made after the fuel was prepared. In Table 11 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 are included in Table 12 and 13. The carbon conversion was 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 11. 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 12. The operating parameters included in Table 12 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 was 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 12. This trend is further illustrated in Figure 35, which is a plot of outlet temperature versus equivalence ratio for Tests 48, 54, and 55. The outlet temperature was 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 33. Outlet Temperature and Emission Characteristics of TSSC Burning CWMs Made From Coals of Varying Particle Size

Emissions are summarized in Table 12 and in Figure 33. The values in Table 12 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 was converted to SO₂. Therefore, neither CO or SO₂ emissions are influenced by coal particle size over this range of test conditions. Figure 33 is a graph of NO_x emissions versus equivalence ratio for the three different coal particle sizes. Figure 33 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 were completed to provide the carbon conversion and particulate emissions data included in Table 12. The analysis of the three samples is included in Table 13. 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 was 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 the size of the coal particles.

The particulate ash and dilution water analyses are also included in Table 13 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 13. 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 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 was $\pm 10\%$ 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 was 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 were 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 was 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 11. 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 12. 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 was 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 12. This trend is further illustrated in Figure 34, which is a plot of outlet temperature versus equivalence ratio for Tests 48, 56, 57, and 58. The outlet temperature was measured at the

Figure 34. Outlet Temperature and Emission Characteristics of TSSC Burning CWMs Made From Coals From Different Seams

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 12 and in Figure 34. The values in Table 12 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 was 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 34 is a graph of NO_x emissions versus equivalence ratio for the four different coal seams. Figure 34 indicates that NO_x emissions are not influenced by coals from different seams significantly.

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 13 indicate that the most efficient combustion was completed burning "S10" from the Upper Freeport seam. The carbon conversion was 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 13 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 12 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 was $\pm 10\%$ for the CWM's tested. The other seams demonstrated slag captures ranging from 23 to 37%. The slag capture values reported in Table 12 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 12 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 were 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 was 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 was 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 with high coal ash lead to faster refractory damage, but do not impact combustor performance while the refractory was intact.

Based on these test results and all earlier tests, the fuel specification for full scale combustor testing has been set and is included in Table 14. These fuel properties do not represent limits for ash concentration, coal loading, etc., but are the 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.

Table 14. 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

3.6 INJECTOR DEVELOPMENT

The original fuel injector used in this program was designed and developed in the previous program. In the TSSC the design fuel flow was 150 pph and the performance was satisfactory. The only obvious shortcoming was the amount of air assist required was approximately 1 pound of air per 1 pound of fuel. This air has to be either supercharged from the compressor discharge or compressed from ambient. Either way power is required which detracts from the overall package performance. An effort was made to improve the atomization by modifying the tip where the fuel and air assist mix as shown in Figure 35. The results of this modification on atomization are shown in Figure 36 and on combustor performance specifically carbon monoxide emissions in Table 15.

When the design was scaled up for a single injector TSSC (flow = 600 pph) or for the full size combustor (4 injector flow = 1500 pph or single injector flow = 6000 pph) it became obvious that the existing design was deficient. The resultant design featured air assist on both sides of the fuel spray introduced through annuli rather than discrete holes. This design was satisfactory for the single

Figure 35. CWM Fuel Injector With Baseline and Modified Air Assist/Fuel Tip

Figure 36. Drop-Size Characteristics of 600 pph Injector

Table 15. Results With Modified Air Assist and Fuel Tip Assembly

	Injector Configuration			
	Baseline		Modified	
Test No.	16	17	25	26 & 27
Fuel	'K'	'K'	'L'	'L'
T _{in} (°)	638	656	649	604
P _{in} (psig)	80	79	76	74
ϕ_{Primary}	1.45	1.04	1.24	1.19
T _{outlet}	1908	1616	1951	1676
Results				
Slag Capture (%)	24	65	---	54
Emissions @ 15% O ₂				
NOx (ppm)	89.2	181	98.4	170
CO (ppm)	113	36.9	0.9	12.7
SO ₂ (ppm)	146	156	128	99.4
Carbon Conversions (%)	98.2 (Test No. 5)			

injector TSSC and both the single injector and 4 injector full size combustor. The air assist requirement was not substantially reduced.

A proposal by Purdue University to study the application of effervescent atomization to the coal-fired gas turbine combustor was received and reviewed. The anticipated advantages were reduced air assist flow (air to liquid ratio ALR) and reduced sensitivity of viscosity on atomization. A subcontract was issued to Purdue to develop design data for an injector for the coal-fired Centaur. Design scantlings were provided to Solar and a set of four injectors were manufactured. Due to the curtailment of the program other than atomization tests the only combustor testing was done on the crude oil evaluation described in Section 3.3. A description of the work done by Purdue is contained in Reference 1.

4.0 CONCLUSIONS

This program set out to prove the technical, environmental and economic feasibility of a DCFGT system for industrial cogeneration applications. The program was curtailed before a proof-of-concept engine test could be carried out. The test results from both subscale and full size rigs demonstrated that the system being evaluated was technically feasible although there remained some combustor related problem areas to be solved including refractory material selection and installation and implementation of a slag removal system in the primary combustor zone. In these areas there are encouraging indications that the problems are not insurmountable.

Environmentally, NO_x levels as low as 30 ppmv corrected to 15% oxygen and CO levels down to 10 ppmv were demonstrated. Control of sulfur dioxide emissions by injecting calcium based sorbents into the secondary zone was shown to be feasible. There were no published limits for these species but the following goals has been established during the program:

NO _x	ppmv @ 15% O ₂	<125
CO	ppmv @ 15% O ₂	<50
SO ₂	ppmv @ 15% O ₂	<75

Economically the major consideration was fuel cost, both of the CWM and the competing fuels such as natural gas and distillates. The lowest projection for the price of CWM meeting the specification that was developed during the program was approximately \$3.00 per million Btu (MMBtu). Diesel fuel at \$1.00 per gallon is about \$7.00 per MMBtu. However most industrial cogeneration plants burn natural gas with distillate fuels used only as backup or standby fuel. Studies conducted during the program indicated that the price of a clean fuel like natural gas or light distillate would have to be at least \$5.70 per MMBtu for a DCFGT system burning \$3.00 per MMBtu CWM to be competitive.

In summary a direct coal-fired gas turbine cogeneration system is not economically competitive at present natural gas prices. Technical problems exist but there does not appear to be any absolute show stoppers at this time. The demonstrated levels for NO_x and CO compare favorably with current levels being stated by gas turbine manufacturers but NO_x as down to 10 ppmv might be difficult for a rich-lean system burning fuels with significant amounts of fuel-bound nitrogen.

5.0 RECOMMENDATIONS

In view of the conclusion that with natural gas prices at their current levels a DCFGT is not economically feasible, the data and information generated by this program should be preserved so that if natural gas prices were to increase to such a level as to make a DCFGT competitive the development does not start at square one.

There are some areas of the combustor that would need immediate attention if development resumed. These include: refractory material selection and installation and implementation of a slag removal system in the primary combustor zone.

While the refractory materials performed satisfactorily in the scale components problems occurred in the full size components. The failures could be due to improper material selection or to installation and curing techniques. The full size combustor is 48 inches in diameter at its largest point. Work in casting and curing these large shapes is needed.

Slag removal systems are not unique to this application so work is being done and could be used if development of a DCFGT resumed.

REFERENCES

1. Sojka, P.F., Santangelo, P.J., Geckler, S.C., Buckner H.N., and Stapleton, S.E., "Effervescent Atomization Applied to the Solar Turbines Coal-Fired Centaur Program", Purdue University, Final Report.

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. A 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	Powhattan	Powhattan with 5.3% Lime	75% Clean Elkhorn 25% Reed Elkhorn
Coal content (wt%)	54.10	56.50	55.50	60.60	49.80	54.08
Ash Content (wt%)	2.10	1.29	1.70	3.40	7.50	1.25
Particle Content						
% Passing 100 micron	100.00		98.80	100.00	100.00	
% Passing 74 micron		98.10	88.70	100.00	100.00	
% Passing 45 micron			80.00	99.50	99.50	99.90
% Passing 37 micron			71.60	98.70	98.70	99.80
% Passing 25 micron			63.70	88.50	88.50	89.30
% Passing 15 micron			55.40	74.00	74.00	80.20
% Passing 8 micron			24.00	38.00	38.00	55.80
% Passing 4 micron						44.70
% Passing 3 micron						33.90
% Passing 2 micron						26.80
% 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	7816	7758	8190	7245
Proximate Analysis (wt%)						
Ash	3.88	2.23	3.03	5.52	13.82	2.30
Volatiles	36.10	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	8.46	8.68	8.16	7.36
Hydrogen	5.80	5.26	4.91	5.25	5.67	5.09
Nitrogen	1.82	1.64	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	46.80	42.80	13.90	53.50
Al ₂ O ₃	28.10	28.00	25.70	22.80	7.60	21.20
Fe ₂ O ₃	11.80	16.20	18.80	20.90	7.10	10.90
CaO	1.36	5.02	5.16	1.91	18.20	4.00
MgO	0.61	1.10	1.39	0.42	11.40	0.06
Na ₂ O	0.91	1.78	0.30	0.59	1.21	2.80
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	0.46	0.67	0.03	0.04	0.20
V ₂ O ₅	0.08	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	2670/2480	2358/2233	2395/2140	3482/2465	2512/2000	2515/2250
Softening	+2700/2605	2393/2286	2530/2275	2502/2480	2544/2193	2665/2275
Hemispherical	+2700/2650	2521/2356	2450/2305	2516/2467	2559/2351	+2700/2350
Fluid	+2700/2700	2555/2494	2518/2495	2518/2495	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	98.80		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	63.40	89.80	80.80	86.60	99.90	95.90
% Passing 15 micron	39.20	73.30	50.80	68.40	91.80	75.60
% Passing 5 micron	22.80	37.30	34.30	37.10	65.20	42.10
% Passing 4 micron		30.00			54.40	31.20
% Passing 3 micron		21.00			40.80	23.20
% Passing 2 micron		15.80			31.80	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	588.00			370.00	435.00
Slurry (Btu/lb)	7288	7094	7043	6975	7156	7084
Proximate Analysis (wt%)						
Ash	3.88	3.88	3.97	4.00	3.26	4.05
Volatiles	36.56	36.52	34.80	37.80	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	8.86	7.61	8.09	7.07	8.11
Hydrogen	5.81	5.43	5.64	5.82	5.28	5.80
Nitrogen	1.58	1.02	1.92	1.86	1.63	2.19
Sulfur	0.82	0.85	0.86	0.72	0.73	0.86
Ash Composition						
SiO ₂	48.50	52.90	42.80	47.60	49.80	44.80
Al ₂ O ₃	29.20	28.00	28.50	27.03	25.10	22.60
Fe ₂ O ₃	15.00	6.85	17.50	15.01	11.80	18.90
CaO	1.74	2.32	1.67	2.53	2.40	3.00
MgO	0.58	0.57	0.59	0.55	0.80	0.01
Na ₂ O	1.38	1.87	2.37	1.55	1.90	1.50
K ₂ O	1.19	1.23	2.65	0.80	1.90	0.80
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	0.26	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	2480/2150	2648/2450	2580/2305	2490/2144
Softening	2650/2475	+2700/2700+	2620/2190	+2700/2480	2650/2285	2661/2345
Hemispherical	2690/2615	+2700/2700+	2630/2300	+2700/2550	2670/2325	2668/2419
Fluid	2700/2805	+2700/2700+	2680/2580	+2700/2585	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	3.68	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	+2700/2635	2694/2419	2640/2355
Hemispherical	2700/2270	2665/2463	+2700/2700+	+2700/2467	2664/2425
Fluid	2700/2474	2673/2486	+2700/2700+	+2700/2651	2680/2467

Coal	U	V	W	X
Source	Kentucky 4A/Blue Gem	Kentucky 4A/Elkhorn		
Coal content (wt%)	54.0	54.46	54.1	54.19
Ash Content (wt%)	2.10	2.99	2.94	3.13
Particle Content				
% Passing 100 micron	99.95	99.97	99.95	99.96
% Passing 74 micron	99.59	99.93	99.88	99.85
% Passing 45 micron	98.45	99.37	98.71	98.16
% Passing 37 micron	97.51	98.63	98.25	85.39
% Passing 25 micron	82.99	72.19	81.55	42.48
% Passing 15 micron	68.97	60.73	66.95	29.88
% Passing 5 micron	37.18	27.21	40.23	22.60
% Passing 4 micron	27.50	18.07	29.58	15.04
% Passing 3 micron	20.85	12.51	22.56	5.31
% 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	10.76
Slurry Viscosity (cp)				
@ 100/sec	200	250	210	280
@ 1000/sec	285	345	305	360
Slurry (Btu/lb)	7094	7110	7064	7057
Coal Characteristics				
Proximate Analysis (wt%)				
Ash	3.84	5.43	5.37	5.72
Volatiles	38.41	34.61	34.33	38.61
Fixed Carbon	59.75	59.96	60.30	57.67
Ultimate Analysis				
Carbon	79.51	83.82	84.16	84.10
Oxygen	12.39	8.19	8.00	7.84
Hydrogen	5.47	5.48	5.60	5.60
Nitrogen	1.71	1.56	1.48	1.60
Sulfur	0.92	0.94	0.76	0.86
Ash Composition				
SiO ₂	46.49	34.90	35.10	42.0
Al ₂ O ₃	26.89	25.49	23.40	24.0
Fe ₂ O ₃	18.14	27.27	30.70	28.2
CaO	2.64	1.29	1.20	1.23
MgO	0.24	0.55	0.53	0.51
Na ₂ O	1.17	0.92	0.63	0.73
K ₂ O	1.12	1.11	1.08	1.13
TiO ₂	0.93	1.14	1.15	1.20
MnO ₂			0.13	0.12
P ₂ O ₅	0.18	0.01	<0.01	<0.01
V ₂ O ₅			0.05	0.05
PbO			<0.01	<0.01
Ash Fusion Temperature (°F)				
Oxidizing/Reducing				
Initial Deformation	2175	2527/2115	2530/2073	2563/2034
Softening	2211	2588/2143	2591/2161	2584/2149
Hemispherical	2496	2632/2210	2600/2269	2593/2434
Fluid	2630	2649/2524	2655/2497	2608/2448

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