**Advanced Coal-Fueled Industrial
Cogeneration Gas Turbine System**

**Annual Report
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ABBREVIATIONS AND SYMBOLS

AMAX	Amax Research & Development Center
B&W	Babcock & Wilcox
CWM	Coal-Water Mixture
DCFT	Direct Coal Fired Turbine
EDX	Energy Dispersive X-Ray
HESR	Hot End Simulation Rig
HWD CSF	Hot Water Dried Coal Slurry Fuel
IBSTF	Integrated Bench Scale Test Facility
MAF	Moisture and Ash Free
PHDL	Pressurized Hydrated Dolomitic Lime
PRIS	Particulate Removal Impact Separator
SEM	Scanning Electron Microscopy
SMD	Sauter Mean Diameter
TSSC	Two Stage Slagging Combustor
UNDEMRC	University of N. Dakota Energy & Mineral Research Center
XRD	X-Ray Diffraction
cp	centipoise
fpm	feet per minute (face velocity - cubic feet gas per minute/square feet filter area)
gal/hr	gallons per hour
MMBtu	million British Thermal Units (based on Lower Heating Value)
MMBtu/hr	million British Thermal Units per hour (based on Lower Heating Value)
msec	millisecond
ppb	parts per billion
ppbw	parts per billion by weight
pph	pounds per hour
ppm	parts per million
ppmv	parts per million by volume
ppmw	parts per million by weight
psi	pounds per square inch
psid	pounds per square inch differential
psig	pounds per square inch gauge
μm	micron

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

1. INTRODUCTION

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

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

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

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

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

2. SUMMARY

This report covers the activity during the period from 2 June 1989 to 1 June 1990. The major areas of work include: the combustor (sub-scale testing and full size design and fabrication), cleanup, coal fuel specification and processing, and the Hot End Simulation rig.

Combustor testing this year on the Two Stage Slagging Combustor (TSSC) rig was devoted to evaluation of a single injector design, development of continuous slag removal approaches, sulfur control through the use of sorbents and assessment of the impact of slurry properties on combustion performance. The single injector combustor design was evaluated as an alternate to the four injector configuration to simplify the design and to improve performance. As a result of this effort fuel injector designs were developed for increased fuel flows which have been used for the full size design. However the single injector combustor did not perform as well as the comparable four injector design.

All the testing to date on the TSSC has been done with a batch slag collection system. Ultimately continuous slag removal systems will be required. Work has been done to develop a water quenched slag pit design combined with a simple lock hopper valve system. Several configurations of the slag pit were designed and tested. Results are promising but areas such as heating of the slag tap still need development.

The TSSC was also used to evaluate sulfur removal through the use of calcia based sorbents. Three different sorbents were tested for their effectiveness. The test results indicate that SO_2 in the exhaust can be controlled through the injection of sorbents into the secondary combustor zone and that the choice of sorbents depends on the level of sulfur in the fuel.

A series of tests were begun to assess the impact of CWM properties on combustor performance. A series of CWM fuels have been prepared by AMAX with organized variations in selected properties to be tested on one configuration of the TSSC. The results from these tests along with results from other tests will be used to finalize a CWM specification.

Based on sub-scale combustor results and full size flow visualization results the full size combustor has been designed and fabricated. The hardware was shipped to the Caterpillar Tech Center for testing at design inlet pressure and temperature. Test facility preparation and combustor rig assembly are in progress.

The Integrated Bench Scale Test Facility (IBSTF) is a one-tenth scale facility which includes all the components of the proposed Coal Combustion System. These are the combustor primary zone, the Particle Removal Impact Separator (PRIS), the combustor secondary zone with sorbent injection system and the secondary filter which is setup to test either candle or bag filter elements. The combustor components used in this rig are the same as those tested in the TSSC. Combustor performance has been the same as on the TSSC or in some cases better due to increased residence time. As indicated below the purpose of this facility is to evaluate the PRIS and the secondary filters.

Testing of the Particulate Removal Impact Separator (PRIS) continued during the past year. Including 12 hours of near continuous operation during the most recent test the PRIS has accumulated over 28 hours of operation on CWM. Ash removal efficiencies of the PRIS and primary zone have been measured as high as 98%. Inspection of the PRIS rods which are alpha sintered silicon carbide tubes revealed severe erosion/corrosion. Analysis of the rods is on-going. A PRIS insert with alumina rods will be installed in the IBSTF for the next round of secondary filter tests. A full size PRIS design has been selected which features a round cross section instead of rectangular to simplify design and reduce refractory stresses. The method of installing the rods has been changed so that the lower end is fixed and the upper end is not, thus reducing compressive thermal stress on the rods. A flow model of this design has been fabricated and is ready for test. The results of these flow visualization tests will be used to finalize the full size design.

The plan for evaluating the secondary filter ceramic barrier elements called for a 50 hour test at design temperature, pressure and stoichiometric flows. During the past year the secondary filter system was assembled with 14 candle filters manufactured by Schumacher. All supporting systems particularly the back purge system were installed and checked out. Several attempts were made to run the 50 hour test. The most recent test was terminated after approximately 12 hours operation on CWM. Prior to switching to CWM a warmup period of about 50 hours using diesel fuel is required. Following this test it was discovered that two of the filters had failed about 6 inches from the top end. The time of failure was not obvious from the pressure drop traces but measurements of particulate removal efficiency indicated the failure(s) probably occurred early in the test before transferring to CWM. Previously two candles had failed after an earthquake of 4.7 magnitude on the Richter Scale had occurred. Also two candles have been broken on the Hot End Simulation rig. All the candles have failed at approximately the location where a transition in material density occurs. The investigation and analysis of these failures is ongoing.

Work on the Coal Fuel Specification Development task has included more than development of a CWM specification and studies of processing methods. Analyses of slag deposits, particulate samples and sorbent materials have been done to support the overall program. The test fuels used have been formulated primarily from eastern Kentucky coals with the exception of a Pittsburgh-seam coal used in some of the sorbent tests. These test coals have had loadings from 50 to 60%, ash contents from 2.3 to 5.5%, a top size of 45 μm with a mean size of 10 μm . Alkali concentrations ranged from 82 to 978 ppm and sulfur contents were up to 3.26%. Fuels without stabilizer were formulated for use on the Hot End Simulation Rig because of problems encountered with gummy deposits in fuel system strainers.

Ash fusion temperatures have been kept below 2700°F for satisfactory slag retention. Additives for modifying ash fusion temperature and slag viscosity were identified.

Processing investigations have continued along with updating of the cost analysis based on processing developments and hardening of the specification. In a parallel effort a study of the feasibility of on-site preparation of the CWM is underway. This study was initiated because of concerns about availability of CWM and transportation and storage problems at the test site.

The effects of the alkali contained in the coal are a major concern for gas turbines. For conventional hydrocarbon fuels the allowable alkali concentration in the gas entering the turbine section is 20 ppbw. A study was made of the fate of the alkali in the parent coal through the preparation, slurring and combustion. This study indicated that alkali sorbents would probably be required to meet the 20 ppb limit. Measurement of the alkali levels in the combustion system exhaust is a problem. Long time exposures of materials to coal combustion exhaust products is needed to assess the effects.

The Hot End Simulation Rig is a scaled down version of the coal-fueled combustor being developed on this program. The purpose is to expose samples of materials and coatings currently used or being considered for use in the Centaur Type H engine to the exhaust products of a coal combustor for extended periods of time. Because the fuel flow is only 2 gal/hr, development of a fuel injector was extensive. Several prototypes plugged readily until the latest version was successfully tested. Most of this year's efforts were concentrated on achieving this goal. Runs of up to 20 hours on CWM have been made. The candle filter was installed and the back purge system checked out. Efforts are underway now to prepare the rig for longer runs which will evaluate the materials. Some of the material samples are air cooled to temperatures representing later stages of the turbine section. The control of the cooling air rates is being automated. Steps are being taken to assure that the sample section temperatures are maintained at design levels.

3. PHASE II - TASK 1 - COMBUSTOR DEVELOPMENT

3.1 SPECIFIC ITEMS OF PROGRESS

3.1.1 Subscale Combustor Testing

- Evaluation of several modifications of a single injector primary zone with a design CWM flow rate of 600 pph has been completed. These tests have provided valuable data for scaling the CWM injectors and have indicated that a single injector concept would not be as effective as the four injector design for the full scale combustor.
- Design and testing of two water quenched slag pits for continuous slag removal have been completed. The first design was to investigate the implications of a water bath below the slag tap hole of the primary zone. This design was for batch type slag collection with capabilities for water circulation. This testing proved that slag could be collected in the water without excessive boiling and with no noticeable impact on the system. The slag collected in these tests indicated that a slag auger/crusher would not be necessary. The second design features a water bath and a lock hopper valve to the side of the pit. This design was to evaluate a simple lock hopping arrangement for continual slag removal. This testing is on-going to improve slag tap heating to ensure slag flow into the water bath. The lock hopper valve has been operated multiple times while burning CWM with no negative impact on the system. The lock hopper design shows promise as a method for slag removal.
- Atmospheric studies of several slag tap geometries have been completed. The design changes have decreased the heat loss from the torches to the water bath. Testing with CWM should be completed in the next several weeks.
- Development work of sulfur removal from the exhaust stream continued with investigations using higher sulfur coals, calcia sorbents mixed with the CWM, and dolomite injection of finer grinds. The results indicate that sulfur loading has a small influence on sulfur capture efficiency, sorbent mixed with the CWM is not effective at lowering the sulfur concentration in the exhaust, and a finer ground dolomite improves sulfur capture slightly.
- A series of tests have been started to assess the impact of different slurry properties on combustor performance. The fuels tested to date are similar in most ways to previously tested fuels with the exception of stabilizer being omitted from one. The absence of stabilizer is observed to retard slag capture and create periods of temperature fluctuations.

3.1.2 Full-Scale Combustor Development

- An evaluation of two full scale combustor designs has been completed. The designs differ in the number of injectors from one to four. The four injector design has been selected. Detailed design drawings have been completed and the hardware has been fabricated.
- Work has been initiated with Caterpillar for testing the full scale combustor at pressures up to 7.8 atmospheres. Accomplishments include selection of a test site, definition of various subsystems required for testing, shipment of the combustor hardware, and design

of the test site installations. Build-up and installation of the full scale combustor is on-going. An initial test date of October 1, 1990 is scheduled.

- Injector development has been completed with injectors ranging from design CWM flow rates of 600, 1500, and 6000 pph. The designs have been evaluated for atomization and spray quality using particle sizing techniques and high speed film and photography. The development work has culminated in the design and fabrication of four 1500 pph injectors that are going to be used in the full scale combustor tests. The 1500 pph injectors have been flow checked with CWM at 1000 pph and have operated as expected.
- The four injectors have been installed in the primary casing for checkout with water. Following checkout the injectors will be sent for casting.
- A flow visualization model of the four injector design has been completed. This model and the single injector model have been operated extensively for comparison. The four injector model has also been run to investigate the influence of injector penetration into the primary zone on aerodynamic stability.
- A full scale fuel skid has been fabricated and checkout has taken longer than expected due to difficulties with the pump controller. The fuel skid controller has been repaired and checkout is complete.

3.1.3 Integrated Bench Scale Test Facility

- This facility has been run over six tests (IBSTF Nos. 4 to 9). IBSTF Nos. 4,5,6, and 7 were aimed at PRIS evaluations and Nos. 8 and 9 were run with ceramic candles in place. Results of these tests as they relate to the PRIS and ceramic candles are included in Section 4.
- IBSTF No. 9 has been completed which was to be a long term (50 hours) CWM burn. The test was abbreviated due to problems with the Moyno pump. During the test 12 hours was logged on CWM and 40 hours on DF#2. The combustion system operated well. Another long term test is being planned.

3.2 DISCUSSION

Component evaluation and development has been conducted on either the subscale Two-Stage Slagging Combustor (TSSC) or the Integrated Bench Scale Test Facility (IBSTF). The TSSC is the original staged combustor consisting of a primary and secondary combustion zone. Recent testing has focused on evaluation of a system for continual slag removal, exhaust desulfurizing sorbents, assessment of a single injector primary zone concept and combustion characteristics of CWMs of differing properties. The IBSTF is a newer facility being used to develop clean-up devices to be incorporated in the full scale engine design. This facility includes identical primary and secondary combustion zone hardware as the TSSC and in addition includes a Particulate Rejection Impact Separator (PRIS) and a Secondary Filtration System, described in Sections 4.1.1 and 4.1.2, respectively. The IBSTF has been operated with coal slurry in a series of six

tests. A summary of recent combustion testing on both facilities is included in Tables 1 and 6. These results are explained in further detail in the following sections.

3.2.1 Subscale Combustor Testing

Single Injector Testing

A primary combustion zone with a single injector is attractive in the design of the full scale combustor for several reasons including less system complexity, lower cost, and potential for higher slag capture. In order to determine if a full scale design with a single injector was feasible from a combustor performance point of view a series of evaluation techniques including subscale combustor testing, atomization studies, and flow visualization were completed. While results from the atomization and the flow visualization studies indicated no significant change in combustor performance going from four injectors to one, the subscale tests indicated the contrary. The subscale combustor tests have indicated that the combustion system still performs well with a single injector, but fails to pass several design criteria required of the combustion system.

This section documents recent subscale combustor tests completed with a subscale single injector primary combustion zone geometry over the past year. Schematics of TSSC with the four injector and single injector primary zones are included in Figure 1. The single injector is designed to flow up to 600 pph of CWM. In the course of testing several modifications to the injector have been made. These injector modifications are shown in Figures 2 and 3. The injector modifications have evolved to improve atomization and ease manufacture of the hardware. Atomization and combustion performance of the 600-1 and 600-2 injectors have been described in LeCren et al, 1989.

In the past year testing has been completed with the injector modifications shown in Figure 3. These injector modifications have been tested in TSSC Test Nos. 39-42. The test parameters and key results are included in Table 1. The 600-3 injector was tested in all the tests except No. 42. The 600-3 features inner and outer air assist with annular fuel delivery. The flow paths of the inner and outer air assist passages are of equal area. The primary air is metered through an annular cone. Testing has been completed in the primary zone with conical walls and the batch slag collection pit. The injector to impactor distance is 16 inches in Test Nos. 39 and 40 and increased to 23 inches in Test Nos. 41 and 42.

The difference between the 600-3 and 600-4 injectors is the height of the primary annulus cone. The 600-4 injector has a shorter cone height and presents a primary air jet of lower velocity at the juncton where the primary air and fuel mix. In both designs the primary air and the fuel spray intersect at an angle ranging from 60 to 90°. In the 600-3 design the primary air velocity overpowers the fuel spray and collapses the spray downstream of the intersection point to a very tight, compact air/fuel jet. The 600-4 design reduces the primary air velocity at the intersection point with the fuel spray so that the downstream air/fuel jet is not as tight and compact. A visual flow check of both injector designs revealed only a slight difference in the spray pattern.

Single Injector

Four Injector

Figure 1. Two TSSC Designs

Prior to testing, the modified 600-3 injector was tested for atomization performance. The modified injector was initially checked out flowing water and air at atmospheric pressure. The spray was allowed to project for a few feet. The spray shape was improved over the 600-2 design in that the spray was centered on the injector's centerline and the spray appeared to be more symmetric and uniform.

The injector was connected to the atomization flow bench for evaluation with CWM at atmospheric pressure. Less than five inches of the spray was viewed. Drop size measurements were made one inch from the injector tip with laser diffraction drop sizing system. The air assist flow was scaled to atmospheric pressure by holding the momentum flux constant. The momentum flux was varied to correspond to a range of air assist flows used in testing and drop sizes were measured at the spray centerline. SMD drop sizes varied from 9 to 41 microns with a value of 12 microns measured at the momentum flux corresponding to the typical test setting. It should be noted that the obscuration of the Malvern laser ranged from 59 to 98%. Data accuracy starts to drop at 65% and can vary by 10% above 90%. At high obscuration measured SMD drop sizes are always

Figure 2. CWM Fuel Injectors for Single Injector TSSC

Figure 3. Schematics of 600 pph Injector Designs Nos. 3 and 4

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 Injector	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 _{out} (°F)	1806	1840	1857	1829	1801	1850	1850
φ _{primary}	1.30	1.29	1.08	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 (0.5089)	121.0 (0.4914)	186 (0.6823)	147 (0.5601)
CO (ppm) (lbm/MMBtu)	12.9 (0.0350)	9.0 (0.0230)	10.1 (0.255)	41.0 (0.1014)	16.5 (0.0408)	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	—	95.0	—
Slag Capture (wt%)	84	84	45	—	32.9	—	—
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.

lowered. However, even if the low end were off by 200% the value (18 microns) is still an acceptably small drop size. A radial profile of the spray indicated a variation of 12 (at the spray centerline) to 18 (at the periphery) microns SMD drop size.

In TSSC Test No. 39 the 600-3 injector was operated for the first time. The 600-2 design was similar except for slightly larger air assist flow passages and hardware that was poorly manufactured. The 600-2 injector performed unsatisfactorily in combustion tests. In Test No. 39 the 600-3 injector showed a marked improvement in combustion over the 600-2, particularly in terms of CO emissions which have dropped from 540 to 150 ppmv @ 15% O₂. The operation was stable after a brief warm-up period of approximately 30 minutes with the operating parameters stabilizing as indicated in Table 1. The injector performance was verified in Test No. 40 where again the outlet temperature started at 1400°F and took about 30 minutes to reach an equilibrium temperature of 1701°F. This lag period is not typical of other subscale combustor modifications which normally exhibit rapid temperature increases (in minutes) to about 1600°F and then climb to a higher equilibrium. One explanation is that CWM is being trapped in the slag pit and not being consumed in the initial part of the test. In both runs the slag pits were filled with unburned carbon and the O₂ levels in the early stages of the CWM run are higher than calculated based on fuel input.

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 _{exit} (°F)	1659	1659	1646	1763	1833	1990
Φ _{primary}	1.20	1.12	1.27	1.25	1.36	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 (0.0068)	2.2 (0.0050)
SO ₂ (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	66.9	54.0	70	—
Heat Input (MMBtu/hr)	4.29	4.32	4.14	4.32	4.70	5.06

*See Appendix A for test fuels data.

TSSC Test No. 41 was run with both an added spool piece in the primary zone and a valve in the outer air assist supply line. The spray pattern of the single injector has a very tight cone angle and the fuel air jet striking the impactor has a high velocity relative to the four injector designs tested. The 600 pph injector (and all injector designs greater than 150 pph) features annular fuel delivery with high velocity air assist on both the inside and outside of the fuel passage. By incorporating a valve in the air assist supply to the outer passage the split of outer to inner air assist can be varied. By diminishing the amount of outer air assist it has been observed that the spray broadens from about three quarters of an inch to 2 inches at its minimum. Atomization studies (LeCren et.al., 1989) with a larger injector where the outer air assist has been varied indicate that only a slight increase in drop size occurs as the outer air assist is diminished. This valve was left in line for Test No. 41 to evaluate if combustion efficiency might be enhanced through diminishing the amount of outer air assist.

In Test No. 41 the inner to outer air assist split was monitored through the supply side air assist pressures. A convenient means of tracking the split of air between the inner and outer air assist is the air assist split ratio which is defined as the ratio of the outer air assist pressure drop across the injector over the inner air assist pressure drop across the injector. This ratio then varies from 1 with the outer air assist valve fully open to 0 with the valve closed. At the start of the run when the valve was partially closed the ratio was 0.4 meaning the valve was more than half closed. The results summarized in Table 1 show an improvement over the other runs with the 600-3 injector.

The emissions are averaged over the entire run even though the air assist split ratio was changed throughout the run. The combustor operated best with an air assist split ratio of about 0.3 to 0.5 in terms of emissions. The NO_x emissions did not vary with this ratio but rather with equivalence ratio. The air assist split ratio had a noticeable influence on the CO emissions varying from a high of 146 ppmv with the ratio equal to 0 to 57 ppmv with the ratio of 0.47.

TSSC Test No. 42 was conducted with the 600-4 injector which has been modified in an effort to enhance primary air/fuel mixing as described above. The ratio of outer air assist pressure drop to inner pressure drop across the injector was held constant at 0.12. The influence of the equivalence ratio on the combustor emissions is shown in the table and further defined in Figure 4 and 5. These figures show the NO_x and CO emissions versus primary equivalence ratio for Test Nos. 41 and 42. The emissions relate to equivalence ratio as expected and previously reported with NO_x emissions rising to a maximum approaching an equivalence ratio of 1.0 while CO emissions drop to a minimum over this same interval. Figure 4 indicates that both injectors operating at design point equivalence ratio for the CFC would produce NO_x emission levels below 100 @15% O_2 (ppmv). The NO_x emissions are similar for both tests 41 and 42 indicating that the changes to the injector had no bearing on them. However, the CO emissions show a substantial drop when using the modified 600-4 injector design rather than the 600-3 injector. Typically, fuel air mixing strongly influences CO emissions rather than NO_x in this type of combustor.

In summary, a series of tests and modifications to a subscale single injector design have indicated that the single injector concept does not operate as well as the four injector design. Modifications to the injector have improved combustor operation in terms of emissions and stability of outlet temperatures and combustor pressure. These tests have indicated that combustor operation is strongly influenced by the following characteristics of the injector.

- Maintaining tight tolerances during manufacture are critical to good injector performance.
- The single injector design creates a spray of fine droplets with the SMD mean drop size below 50 microns.
- The ratio of air assist delivered to the inner and outer passages in the injector tip have a strong influence on CO emissions and hence combustion efficiency. The best results were obtained with the outer air assist receiving 50% of the inner air assist flow.
- Better mixing of the primary air and fuel is obtained by allowing the injector tip to protrude past the primary air metering ring. As this happens the air/fuel jet is broadened. CO emissions and combustion efficiency are improved as the primary air ring is raised relative to the injector tip.

Continuous Slag Removal

Development work has been started and much has been completed in the area of continuous slag removal. Design and test work has been completed primarily for the subscale TSSC. The development path for continuous slag removal has been 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. Work has proceeded with the first two parts completed and the third nearing completion.

Figure 4. Comparison of NO_x Emissions Using Two 600 pph Injector Designs

Figure 5. Comparison of CO Emissions Using Two 600 pph Injector Designs

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 has been 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 the combustors 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 is now on-going on a simple lock hopper arrangement. Key results to date indicate 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 being pursued is 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 6. The slag pit has a refractory lined upper half and exposed steel case on the bottom. The slag tap hole is 4 inches in diameter. Three of Solar's Saturn engine torches are 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 is introduced through the upper pipe and exits through the lower pipe. Water is circulated to prevent boiling. The water level is controlled manually by watching the 12 thermocouples located immediately above and below the water line. The water flow rate is 3 to 5 gpm through the slag pit. Water that exits through the outlet pipe passes through a filter to collect any particulate and slag that is 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 have been 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 is also 99.8% ash and 0.2% carbon. The remaining slag pit contents were unburned carbon which is 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 is 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 is used to fill a lock hopper with periodic flushes of the slag pit contents. The system, illustrated in Figure 7, features a torch heated slag tap hole,

Figure 6. Water-Flushed Slag Pit

Figure 7. Baseline TSSC With Water-Quenched Slag Pit

a water bath, a discharge pipe, an isolation ball valve, and a lock hopper. During combustor operation the slag removed from the primary zone flows through the slag tap hole and drips into the water bath, freezing instantaneously. The water bath has both inlet and outlet pipes for continuous water circulation to prevent boiling. Slag collected in the water bath sinks to the bottom of the discharge pipe. After a given time period the isolation valve is rapidly opened and closed to fill the lock hopper with water and slag. The lock hopper can be charged with air pressure to control the pressure drop taken across the isolation valve.

The test hardware has been designed to fit the existing TSSC rig which requires that a very tight height requirement be placed on the slag removal system. The discharge pipe axis is at a right angle to the combustor centerline. One end of the discharge pipe is capped and the other is connected to the lock hopper with a isolation valve in between. In the full scale combustor a lock hopper can be positioned directly beneath the water bath and isolation valve without 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 can be proven to effectively remove slag than the scaled design will function even more effectively.

The isolation valve and lock hopper arrangement has been run in two tests. TSSC Test Nos. 45 and 46 were run at typical test conditions burning CMW 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 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 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 have been completed at atmospheric pressure running the torches only. The slag tap geometries tested are shown schematically in Figure 8a to 8e. 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

A. WATER BATH AND BATCH SLAG PIT

B. DESIGN #1. SUBSCALE WATER QUENCHED SLAG REMOVAL SYSTEM

C. DESIGN #2. SLAG REMOVAL SYSTEM WITH LOWER HEAT LOSS REFRACTORY

D. DESIGN #3. SLAG REMOVAL SYSTEM WITH RADIANT HEAT SHIELDS

E. DESIGN #4. SLAG REMOVAL SYSTEM WITH LARGER SLAG TAP TO WATER BATH DISTANCE

Figure 8. Slag Test Geometries Tested

Figures 8b 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 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 has been 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 will be tested in TSSC Test No. 47 for performance characterization.

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>			2432
Slag Tap (°F)	2050	2345	
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.			

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

Sorbent Evaluation

The sorbent evaluation test plan has been completed with several more subscale tests in the TSSC. The test set-up and procedure has been 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 has been used in most testing. The principle difference between CWM 'F' and 'G' are that 'G' has been 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 SO_2 baseline data without any sorbent addition including collecting and analyzing slag samples; and secondly, to evaluate dolomite for sulfur capture at higher SO_2 concentrations.

The data taken while burning CWM 'F' is graphically summarized in Figures 9 and 10. Figure 9 shows the SO_2 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 is calculated as the measured SO_2 without sorbent injection minus the measured SO_2 with sorbent injection. This data indicates that a slight increase in sorbent effectiveness is realized as coal sulfur loading is

Figure 9. SO_2 Reduction of Dolomite Injected in the Secondary Zone of the TSSC Burning CWMs of Varying Sulfur Loading

Figure 10. SO₂ Emissions at Varying Ca/S Ratios of Dolomite Injection

increased. The result has 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 10 and coincide with the data presented in Figure 1. In summary the dolomite effectiveness at a Ca/S ratio of 3.0 is 63% reduction in the SO₂ level. This reduction still leaves an SO₂ concentration of 200 ppmv which is 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 10) would be required.

One test (Nos. 36) has been run 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.

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 is less than 2%. The reduction based on theoretical emissions is 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 is removed with the slag. This result supports that sulfur capture by the calca in the primary zone is poor. Another serious consequence of mixing the sorbent with the CWM is that calcium reacts with the aluminosilicate

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 3.

The results of testing with this sorbent compared to dolomite tested previously with a larger particulate size are shown graphically in Figure 11. In this figure, SO_2 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 is 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 SO_2 reductions. The results suggest that using finely ground dolomite offers only a slight advantage over coarse grinds in terms of SO_2 reductions.

In summary, recent testing evaluating sorbents for sulfur capture have indicated that a slight improvement in sorbent sulfur removal efficiency is 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 SO_2 reductions. Particle size of the sorbent does have a strong influence on sulfur capture, however not as strong an influence as predicted by others.

Test Fuels

A study has been started to examine key CWM fuel properties influences on combustor performance. Testing has been completed to date to study the influence of stabilizer on combustion in TSSC Test Nos. 43 and 44. Properties of the CWM fuels are listed in the Appendix.

The fuel burned in Test No. 43 is CWM 'S1' which is the baseline fuel for these fuel property tests. The properties of 'S1' are similar to fuels recently tested for other development activities with 54.5% coal loading, 1.89% ash, and a particle top-size of 45 microns. 'S1' has been designated the baseline fuel in this study, meaning that the fuel characteristic being examined will vary off this basic formulae. CWM 'S2' is identical to 'S1' except during preparation 'S2' was made without the addition of "stabilizer". These fuels are described in greater detail in Section 5.0. Both tests were conducted in the baseline TSSC, which includes four dome mounted injectors, a seven inch straight-walled primary zone spool, a 14 inch conical primary zone spool, and a batch slag collection pit.

The test conditions and operating results are summarized in Table 1 for these two tests. The combustor ran well with both fuels. As Table 1 indicates little difference can be seen in the emissions and outlet temperature. Particulate samples have been taken during both tests with a slight drop in carbon conversion efficiency testing CWM without stabilizer.

Table 3. Properties of Dolomite of Different Grinds

	Dolomite D-303	Dolomite D100
Composition, %		
SiO ₂	0.65	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	0.004	—
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 11. Comparison of SO₂ Reductions of Dolomite of Varying Sizes Injected Into the Secondary Zone

Only two differences in combustor performance have been identified in testing with these two fuels. First, as seen in Table 1 the slag capture dropped off considerably going from fuel containing stabilizer to fuel without. The determination of slag capture is only accurate to within 10%, and in shorter tests (2 hours) such as these the error could potentially be the full 10%. However, a real benefit from the addition of stabilizer to the fuel in terms of slag capture is indicated by the data. This observation is contrary to expectation. Stabilizer has been observed by workers at Sandia Labs to promote particle agglomeration during the atomization process. Agglomeration creates an effectively larger char particle that takes longer to fully combust. In these tests where available combustion residence time is fixed the fuel that can be the most finely atomized should require the least combustion time, providing the best combustion performance. As shown in Table 1 this is not supported by the data. Furthermore, for slag capture it indicates the opposite is true.

The other difference in using a fuel without stabilizer observed in Test No. 44 was intermittent outlet temperature drops. On four occasions during the two hour CWM run the outlet temperature was seen to drop by 200 to 300°F over a few minutes only to rebound to the temperatures before the drop. The fuel flow rate as indicated by the micromotion did not vary nor did the air flow rates. The operation could be explained by the rapid settling of coal in the fuel reservoir that created pockets of fuel with a lower coal loading, however this is unproven.

In conclusion, these tests indicate that the addition of stabilizer to the CWM improves both the fuel handling and the slag capture. The addition of stabilizer to the fuel does incur an additional cost and in that light is undesirable.

3.2.2 Full Scale Combustor Development

Combustor

The full scale combustor has been selected, detailed and fabricated in this reporting period. The assembly drawing, shown in Figure 12, features four CWM injectors and a batch slag pit. The selection of a four injector design over a single injector design has been made as a result of subscale combustor testing, full scale flow visualization, and atomization studies of full scale injector hardware. The subscale combustor testing has been described in Section 3.2.1 and the full scale atomization and flow visualization results are discussed below.

The four injector full scale combustor primary zone design includes elements that have proven beneficial in subscale testing. Included in this design are a primary zone with conical walls, an impactor supported by ribs above the slag tap, injectors angled to create a central jet with adequate residence time between the injectors and impactor for combustion of a large percentage of the CWM, and refractory lined walls. A comparison of the full scale and subscale primary combustion zone geometries are included in Table 4. The distance the injectors penetrate into the primary zone has been narrowed through flow visualization studies, so that two distances can be studied in combustion testing. The primary zone is cast with three types of refractories to minimize heat loss through the casing. In the subscale combustor only two materials were used. The primary zone is expected to perform as well or better than the subscale combustor.

The slag removal from the primary combustion zone of the four injector design is on a batch basis for preliminary testing. As the continuous slag removal system is developed on the subscale a slag removal system design will be generated and incorporated into the full scale combustor.

Table 4. Primary Zone Scaling

	Bench-Scale	Full-Scale
Volume (in. ³)	3,695	37,675
Residence Time (msec)	150	200
Dimensions (in.)	18 x 14 ϕ to 19 ϕ	36 x 22.5 ϕ to 49.5 ϕ
Weight (lb)	1,450	20,950

Figure 12. Full-Scale Combustor

The secondary combustor is scaled directly from the subscale model. Table 5 compares the geometries of the full and subscale designs. Both designs feature six air inlet ports angled at 37° from the combustor centerline. The secondary zone is refractory lined with two materials to minimize heat loss.

Table 5. Secondary Zone Scaling

	Bench-Scale	Full-Scale
Volume (in. ³)	680	6,810
Residence Time (msec)	50	50
Dimensions (in.)	12 x 8.5φ	26 x 18.25φ
Weight (lb)	200	2,960

All full scale combustor casing components have been designed to the intent of ASME boiler code. The anticipated maximum skin temperature on the vessels is 400°F. All hardware is hydrostatically pressure checked to 225 psig.

Fabrication of the full scale combustor is complete. The hardware is pictured in Figure 13. Most of the hardware has been shipped to Caterpillar Technical Center in Peoria, Ill. for assembly in preparation of full scale testing.

Figure 13. The Full-Scale Combustor

Injector Development

Full scale injector development has been completed of injectors capable of flowing 1500 pph and 6000 pph for the four and single injector primary zone designs, respectively. The injectors are the same conceptual design as described in Section 3.2.1 for the single subscale injector (600 pph). These injectors have been flowed and inspected for atomization and spray characteristics. To flow these injectors a fuel skid for the full scale combustor tests has been designed, tested, and fabricated. The four 1500 pph injectors have been installed in the injector spool and flow checked with water and air. All results indicate that the injectors should work well in the full scale combustor to provide superior combustion performance.

In the injector designs CWM fuel is delivered through an annular passage surrounded on both sides by high velocity air assist for atomization. Primary air is delivered through a conical annular metering passage created by the placement of the injector head within the injector cone. The 6000 pph injector head is pictured in Figure 14. The injectors are made of 304 stainless steel. The outside of the injector bodies are insulated with a refractory casting.

The 6000 pph injector head was evaluated first for atomization quality. Previous testing and observations at a CWM flow rate of 430 pph have indicated that the injector generates a spray which is largely symmetric but does show some asymmetry and large drop generation at the spray periphery. At this flow rate the injector was evaluated at atmospheric pressure in the atomization rig. Results taken indicate that CWM SMD drop sizes of 30 to 75 microns are produced by the injector run at 430 pph and air assist/fuel mass ratios of 1.0 to 1.5. As the flow was increased to 1000 pph (still one-sixth of design point) the spray looks noticeably more uniform and symmetric. Efforts to take drop size measurements have been unsuccessful because of laser obscuration above 97% at all points in the spray.

Figure 14. 6000 pph Injector Head

The spray has been photographed both with still pictures and using the high speed film camera. Photographs of the injector spraying at 430 and 1000 pph are included in Figures 15 and 16, respectively. In the photos the asymmetry of the injector flowing at 430 pph is evident. Contrasting this with the injector flowing at 1000 pph shows a considerable improvement in spray uniformity. The high speed film supports the photographs indicating that the flow at 430 pph is unsteady around the spray perimeter, but becomes much more steady at 1000 pph.

The 1500 pph injectors were fabricated and delivered to Solar. The injectors were checked for manufacturing tolerances and are within all design specifications. The injectors were installed on the air flow bench to determine the primary orifice effective area. After several iterations of setting the primary annular gap the desired effective area of 2.51 in² per injector has been obtained.

The 1500 pph injectors were checked-out at flow rates of 1000 pph. The CWM sprays were evaluated with high speed film and photography. The optical denseness of the spray prevents the use of droplet sizing systems such as the Malvern to determine spray size distributions. The injectors are being operated and compared to studies completed with previous scaled injectors which have been evaluated in a combustion rig. Visual spray characteristics such as cone angle, uniformity, and spray pattern are compared.

All the 1500 pph injectors have been sprayed and photographed. Pictures of sprays for two injectors is included in Figures 17 and 18. The camera is set to take an exposure of 1/30,000 of a second. It is evident that this time interval is too long to "freeze" the spray. The picture does

Figure 15. 6000 pph Injector Head Spraying 430 pph of CWM

Figure 16. 6000 pph Injector Head Spraying 1000 pph of CWM

Figure 18. 1500 pph Injector No. 1 Spraying CWM at 1000 pph

Figure 18. 1500 pph Injector No. 4 Flowing at 1000 pph at an Exposure of 1/30,000 of a Second

illustrate that the injectors create well dispersed, uniform sprays with an approximate 12° cone angle. The sprays do not vary with the four different injectors. High speed film supports these conclusions showing the sprays to appear uniform and steady at exposures of 1/10,000 of a second. Based on these techniques and comparisons to previous studies of scaled injectors where both photography and drop size measurements were employed the spray mean drop size is estimated to be between 25 and 50 microns. The injector is expected to perform adequately during combustion tests.

The four injectors have been installed in the injector spool as shown in the photograph, Figure 19. Primary air and air assist supplies were connected to the manifolds to allow a flow check of all the injectors simultaneously. Water flowing at total rates of 6000 to 8000 pph was used rather than CWM due to test site limitations. The injectors were flowed with water only initially to evaluate distribution to the four injectors. All the injectors were found to flow within 3.3% of the average flow rate with the largest flow discrepancy between any two injectors being 6.4%. These measurements are within design expectations for these injectors. The spray generated in these tests is shown in Figures 20 and 21. Figure 20 shows the spray looking up to the injectors. Jets of water and air can be seen merging to create one central jet. All the jets were steady with no

Figure 19. Full-Scale Hardware Set-up for Flow Checkout of Four Injectors

variation between the injectors. Figure 21 shows a broader view of the spray generated by the four injectors. In this shot the injectors are inside the casing slightly above the top of the photo. The spray is flowing downward. The spray is uniform and well centered. These results further confirm that the combustor should perform as expected.

Flow Visualization

Another tool used to determine whether the full scale combustor should be designed with four or one injectors is flow visualization. Full scale flow visualization models of both the single and four

Figure 20. Water Spray Generated by Four Injector Full-Scale Hardware Showing the Merge of Four Jets

Figure 21. Intersection of Sprays From Full-Scale Combustor Hardware

injector primary zone geometries have been fabricated. These models, shown in Figures 22 and 23, are made of plexiglass. Air is drawn through the models with a vacuum at rates such that the inlet velocity at the injectors is identical to that velocity at full pressure. The airstreams are traced with neutrally buoyant helium filled soap bubbles injected into the inlet air supply. The operation of the model is documented with photography, video tape, and high speed film.

The full scale single injector combustor flow model was run initially. These observations indicate that the combustor generates a strong, symmetric toroidal air pattern as predicted. A photograph of the flowing model is included in Figure 24. The central air jet is strong and coherent striking the impactor at the center. The recirculation zone is very tight which should promote rapid fuel-air mixing for efficient combustion. The injector was elevated four inches and the flow pattern observed again with no obvious difference in the flow pattern. This adjustment was made to maximize the available burn-out time of the coal in the central jet.

A model of the four 1500 pph injector full scale combustor design has been fabricated and run. The model also exhibits a strong central jet with tight recirculation zones. A photograph of the flowing model is included in Figure 25. Examining the flow pattern around the injectors showed that a small secondary recirculation zone slightly below the injectors was generated. This recirculation zone is not expected to appreciably impact the combustor's performance. Based on subscale combustor testing and flow visualization modelling, the performance of the four injector full scale combustor should be similar to the subscale rig.

Figure 22. Single Injector

Figure 23. Flow Visualization Model of Four Injector Full-Scale Combustor

Figure 24. Single Injector

Figure 25. Flow Visualization of Four Injector Full-Scale Combustor Design

The depth the injectors protrude into the primary zone has been varied on the four injector model to inspect the flow pattern for any variations with injector depth. The preliminary design had the injectors protruding into the primary zone six inches from the wall measured along the injector centerline. This distance is based on the subscale combustor design. The injectors are desired as close to the wall as possible to limit the length of injector refractory exposure to primary zone gases and to maximize the injector to impactor residence time to facilitate char burn-out. The model has been tested with injectors at 0 in., 3 in., 4.25 in., and 6 in. from the wall. With the injectors at 0 in., a sharp degradation in the flow pattern is observed. The central jet is not as strong and precesses over the top of the impactor. The recirculation zones are also not steady. As the injector depth is increased the pattern steadily improves. The depth the injectors will protrude in the primary zone has been set at three inches with provisional hardware fabricated to test at six inches as required.

Full Scale Combustor Testing

Planning and preparation for full scale combustor testing at the Caterpillar Tech Center in Peoria, Ill. is well underway. Major accomplishments include selection of a test site, definition of combustor subsystems, definition of a schedule to complete test site preparations, fabrication and shipment of most of the combustor hardware, and initial installation of the combustor hardware at the test site. Start-up and testing of the full scale combustor is expected to commence in October, 1990.

The location for testing the full scale combustor has been selected to be in the service bay in the compressor room of Building E at the Tech Center. A layout of the service bay with the full scale combustor design installed is shown in Figure 26. This location was selected because of the ample space it provides. This location will allow for insertion of the full scale PRIS as shown in Figure 27 with ample space still remaining. The primary disadvantage with this location is the lack of standard test cell instrumentation and a supply of high pressure heated air. Planning to make these installations available is underway and fabrication has been started.

A block diagram of the system with all the subsystems is shown in Figure 28. The diagram indicates whether the subsystems are going to be supplied by Solar or the Tech Center. The major subsystems that have been identified include the combustor hardware, the air supply, the fuel delivery system, exhaust treatment, water supply, and instrumentation/DAS. Solar has supplied most of the combustor hardware and the fuel skid will be delivered shortly. Subsystems being put together by the Tech Center are in progress with work assignments complete. The longest lead item shown is the air supply which is still in the planning stage.

3.2.3 Integrated Bench Scale Test Facility

In this reporting period the IBSTF was run in six hot combustion tests. IBSTF Test Nos. 4 to 9 have been completed burning CWM and diesel fuel. The focus of these tests has been in evaluation of two clean-up devices required for the successful operation of the CFC. These devices are the PRIS and the Secondary Filter. The performance of these clean-up elements in these tests is described in detail in Sections 4.1 and 4.2. This section describes how the combustion system worked in integration with the clean-up devices.

Figure 26. Four Injector Combustor Without PRIS as installed at Test Site

Figure 27. Full-Scale Combustor and PRIS Installation at Test Site

A summary of test conditions and results of these tests is included in Table 6. The primary objective for Test Nos. 4 to 7 was for evaluation of the PRIS. These tests were run without the filter elements installed in the secondary filter. IBSTF Test Nos. 8 and 9 were run with ceramic candle filters in place. Test No. 9 is the most recently completed test and was a longer term operation of the system on CWM.

IBSTF System Operation

During tests of the IBSTF it has been found that in comparison to the TSSC the operation of the IBSTF is superior. Comparing Tables 1 and 6 improvements in combustion can be seen in gaseous emissions, carbon conversion, and sulfur capture efficiency with calcia sorbents. In operation the IBSTF exhibits a steadier operation in terms of combustor pressure and outlet temperature fluctuations. As an example of this observation, a back pressure valve which is used to regulate the combustor pressure typically requires adjustment every 10 to 40 minutes in the TSSC, while in the IBSTF this adjustment is only required every 40 to 120 minutes.

Figure 28. Full-Scale CFC Combustor Test Site Block Diagram

Table 6. Summary of CWM Testing In the IBSTF

Test Facility	IBSTF	IBSTF	IBSTF	IBSTF	IBSTF	IBSTF
Test No.	4	5	6	7	8	9
Objective	PRIS Evaluation	Particulate Emissions	PRIS Evaluation	PRIS Evaluation	Candle Filters	Candle Filters
CWM*	'N'	DF #2	'N'	'N'	'T'	'H'
CWM Burned (lbs)	1279	---	>500	1601	1870	6921
T _{in} (°F)	570	635	---	603	614	641
P _{in} (psig)	76	80	---	80	82	80
Secondary Zone T _{outlet} (°F)	1781	2059	---	1829	1933	2016
φ _{primary}	1.22	1.40	---	1.21	1.26	1.39
T _{pr} (°F) outlet	2587	2967 ¹	---	2633	2654	2697 ²
T _{filter} (°F)	---	---	---	---	1570	1315 ²
NO _x (ppm) at 15% Oxygen (lbm/MMBtu)	52.2 (0.2100)	25.0 (0.2390)	---	47.2 (0.192)	29.0 (0.1175)	23 (0.0905)
CO (ppm) at 15% Oxygen (lbm/MMBtu)	22.5 (0.01)	---	---	13.0 (0.033)	10.3 (0.026)	5.27 (0.0143)
SO ₂ (ppm) at 15% Oxygen (lbm/MMBtu)	156.9 (0.89)	---	---	181.6 (1.025)	49.2 (0.2759)	90.8 (0.5234)
ΔP/P Primary (%)	3.0	3.9	---	3.8	3.6	3.5
ΔP/P PRIS (%)	1.03	0.7	---	1.0	1.4	1.13
Carbon Conversion (%)	99.9	---	---	99.8	99.9	---
Slag Capture (wt%) (Primary and PRIS)	---	---	---	97.1	98	---
Heat Input (MMBtu/hr)	4.12	4.07	---	4.21	5.19	4.68
<p>* See Appendix A for test fuels data. ¹ Inlet Temperature. ² See Figure 30.</p>						

The IBSTF has been run in Test Nos. 4 to 6 for PRIS evaluation and system shakedown. While these runs did expose the PRIS to coal combustion, system corrections were made to set the primary to secondary air flow split, improve instrumentation durability, to increase the capacity of the exhaust piping, and resolve permitting issues for San Diego County APCD. The procedure for these tests was supposed to be to warm-up on DF#2 for four hours with gradually increasing operating temperatures, CWM combustion for three to four hours at constant operating conditions, and to end the test by switching back to DF#2 with gradually decreasing operating temperatures over an additional hour. During CWM combustion the operating conditions are inlet air at 620°F, combustor pressure of 80 psig, and combustor pressure drop ratio of 4%. In actuality, none of these tests were run following the test procedure at the specified conditions. While results from these tests indicate excellent combustion characteristics, it should be noted that either the operating settings were slightly off or the test was terminated prematurely.

In IBSTF Test Nos. 7, 8, and 9, operation was completed at the design settings for longer than three hours on CWM. In Test Nos. 7 and 8, CWM was burned for three hours and in Test No. 9 the combustor was operated for about 52 hours with 12 of those hours on CWM. Comparing results from these tests with test results taken in the TSSC, the improvements in gaseous emissions are evident. Gaseous emissions taken in the IBSTF are sampled downstream of the secondary combustor in tests without the filter in line and downstream of the filter vessel with the filter in line.

The emission data are further detailed in Figures 29 and 30 which show the NO_x and CO emissions versus primary combustion zone equivalence ratio, respectively. These figures show the emissions from the IBSTF compared to the emissions measured from the TSSC. Included in these graphs are straight lines which indicate the design goal of the CFC. For NO_x this emission goal is 125 ppmv @ 15% O_2 and for CO the goal is below 50 ppmv. These goals are set based on the NSPS for gas turbine in the size range of the Centaur Type H burning distillate fuels with an allowance for fuel bound nitrogen. The goals are more strict than NSPS. Clearly a benefit is seen for lowering the NO_x emissions in the IBSTF rather than the TSSC. Both rigs have demonstrated NO_x control below design goals at the design point equivalence ratio of 1.30. The principle difference between the two test rigs is the PRIS in the IBSTF. The PRIS adds extra residence time for rich zone combustion. An explanation for the reduced NO_x emissions is that with added residence time for rich zone combustion the char is more fully converted to gaseous species and the gas mixture entering the secondary combustion zone is more homogeneous and well mixed. Upon entering the secondary zone this homogeneous mixture is rapidly mixed with the secondary air and the combustion process is completed without the creation of local "hot spots". Uneven flame temperature in a combustion zone has been shown to produce higher NO_x emissions.

The CO emissions do not vary between the IBSTF and TSSC. Both rigs demonstrate CO emissions well below CFC goal at 10 ppmv at an equivalence ratio of 1.30. Low CO emissions are primarily a function of the residence time/temperature relation downstream of the secondary combustion zone and the combustion efficiency of the primary zone. These results indicate that both test rigs allow adequate residence for complete combustion.

The carbon conversion is above 99.8% for these tests at design settings. The carbon conversion is measured from particulate samples taken in between the secondary combustion zone and the secondary filter vessel. A failure of the particulate probe prevented making this measurement in

Figure 29. NO_x Control in CWM-Fired Subscale Test Rigs With and Without Hot Gas Clean-up

Figure 30. CO Control in CWM-Fired Subscale Test Rigs With and Without Hot Gas Clean-up

Test No. 9. The IBSTF demonstrates slightly improved carbon conversion over the TSSC. This result tends to confirm the assertion above that the added residence time in the PRIS allows for more complete char conversion.

Sorbent was injected continuously during Test Nos. 8 and 9 to determine sulfur capture efficiency in the IBSTF. In both tests dolomite of 50 mesh was injected at a constant auger speed setting. A difficulty persists in accurately measuring the sorbent feed rate into the system. In Test No. 8 an average feed rate of 15.7 pph has been calculated based on the total sorbent batch lost from the feed tank divided by the test interval. Determining the sorbent tank weight during the test continues to be difficult because the flex hoses used to convey the sorbent into the secondary air supply exerts force on the tank as a function of the system pressure which alters the measured tank weight. In Test No. 9 the average sorbent feed rate has not been determined.

The SO_2 reduction results for data taken in Test No. 8 are summarized in Figure 31 which shows the SO_2 reduction versus Ca/S ratio. Also included in the graph is the dolomite sulfur removal effectiveness data taken in the TSSC. The box indicates the error band in measurements for this test which as mentioned above, are significant. The SO_2 emissions data are taken downstream of the secondary filter vessel. The graph shows an improved level of sulfur control in the IBSTF versus the TSSC. In the IBSTF the piping and the secondary filter increase the available residence time for sorbent-sulfur reactions. Calculating the available residence time is difficult because the sorbent creates a "cake" on the filter elements. This cake will continue to capture sulfur until a purge cycle is initiated on the filter elements and the particulate "cake" is removed.

Figure 31. Dolomite Injection In Secondary Zone for Two Test Rigs

Long Duration Testing

IBSTF Test No. 9 was the longest test on CWM at this scale. As an operating system much was learned during the test. During the test a total of 40 hours was run on DF#2 and 12 hours on CWM. The operating conditions and results during CWM combustion are summarized in Table 6. Heat-up of the rig was completed with combustion of DF#2. To facilitate heat-up diesel fuel was injected in the primary and secondary combustion zones this was done to obtain high secondary combustor outlet temperatures without burning fuel rich with DF#2 in the primary zone, which has caused refractory damage in other tests.

A temperature-time history of the test is included in Figure 32. In this graph temperature measurements taken at the PRIS outlet, secondary combustor outlet, bypass tee, filter inlet, inside the filter vessel, and at the filter outlet are graphed versus the hour of combustion. The graph shows data taken after 28 hours of diesel combustion. The temperatures had reached equilibrium at the levels shown at the 28 hour mark. During diesel combustion at the 24 hour mark the rig was shut-down due to a large hole in the exhaust cyclone. The rig was up and running within one hour and quickly reached equilibrium again. As the graph indicates the rig was shut-down on one other occasion during the test at 33 hours. Due to problems with the moyno CWM pump the system was switched back and forth between CWM on four occasions. Other difficulties encountered during the test include: erosion and leaking of piping downstream of the back pressure valves, disconnection of the CWM feed line, over tempering of piping on the PRIS housing and bypass reducers, and breakdown of the vacuum pump in the emissions sampling system.

Starting at 39 hours and continuing to 48 hours, the system was run continuously on CWM. This is the period in which the data in Table 6 is derived. As Figure 30 indicates, the system was rapidly approaches equilibrium with temperatures at the PRIS outlet of 2750°F, the secondary combustor 2025°F, inside the filter vessel of 1810°F, and exiting the filter of 1525°F. These temperatures indicate that although heat loss from the system has been reduced, the piping from the secondary combustor to the filter, a temperature drop of 200°F still exists. The filter vessel tubesheet is also removing more heat than desired as indicated in the graph and explained in Section 4.2.

Post-test inspection of the combustor primary zone and secondary zones show that refractory works well in the cooler secondary zone but has problems in the hotter primary zone. The primary zone refractory, particularly in the conical section and the impactor, has eroded/melted substantially. The slag pit contained a 17.5 lb slag "stalactite". The impactor was surrounded by 64 lbs of slag and refractory with only the top center still visible. The maximum slag capture by the primary zone is 81.5 lbs which would indicate a slag rejection of 94%. However, since part of the slag is melted refractory, this value is most certainly high. The fact that slag did not fully drain into the slag pit is not surprising in light of the upsets during the test. These upsets may also account for the damage to the refractory in the conical section because transition to and from diesel combustion was not always as "smooth" as desired. Damage to refractory in the remaining parts of the primary zone, primary zone to PRIS transition elbow, PRIS outlet, and secondary zone was very light.

Figure 32. Temperature Time History at Different Stages in the IBSTF While Burning CWM in Test No.9

Test Site Permitting

Another issue that has received a great deal of attention in the operation of the IBSTF in this reporting period is in meeting local San Diego county pollution control ordinances. In order to obtain a test permit, the test facility has to demonstrate particulate emissions below 0.1 grain/DSCF @ 12% CO₂ (177 ppmv @ 15% O₂), SO₂ emissions below 363 ppmv dry @ 3% O₂ (121 ppmv @ 15% O₂), an visible emissions from the stack of less than 20% opacity. The CFC is designed to meet and exceed all these emission constraints. The IBSTF has passed all the constraints except for the particulate emissions. In the IBSTF only 30% of the total system flow passes through the secondary filter vessel and several tests were run without the filter in line. Making matters worse it was discovered that the high pressure air supply is extremely "dirty" accounting for almost half of the particulate emissions when no injecting dolomite. These factors lead to particulate emissions in excess of 4 times the allowed limit. The facility features an exhaust cyclone, but is apparent that more clean-up is required in the quench zone. A venturi scrubber is under fabrication and will be installed for the next test.

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

4.1 SPECIFIC ITEMS OF PROGRESS

4.1.1 Post-Primary System

- Subscale PRIS is installed in the IBSTF for the next series of tests.
- The subscale PRIS containing silicon carbide alpha sintered ceramic tubes has been exposed to CWM combustion in IBSTF Test Nos. 4 to 9. The ash removal efficiencies have been measured to be as high as 97.4%.
- The subscale PRIS has been exposed to CWM combustion in IBSTF No. 9 for 12 hours of near continuous operation. Post test inspection of the rods indicates severe corrosion/erosion took place. Even with this damage the PRIS still removed a large quantity of slag. Analysis of the rods is on-going.
- A flow visualization model of the subscale PRIS has been fabricated to evaluate design parameters for potential application to full scale PRIS design. The model has been run using table honey as a slag simulant indicating that the PRIS is capable of removing 99% of this material.
- A full scale PRIS design has been selected that features seven rows of 1.25 inch diameter solid rods. The PRIS duct geometry has been changed from rectangular to circular to simplify the design and reduce refractory stresses. The detail drawings for the full scale PRIS have gone through final check-out.
- Fabrication of the flow visualization model of the full scale PRIS is complete. Installation in the test cell is nearing completion.

4.1.2 Post-Secondary System

- Candle qualification testing was conducted at Solar and consisted of extensive scanning electron microscopy with energy dispersive X-rays (SEM/EDX) of two unused candles manufactured by Schumacher.
- The tubesheet surfaces were re-instrumented with 22 thermocouples, 11 on each side.
- Twenty Schumacher dia-Schumalith candles were cast into Hastelloy-X cups using a refractory bonding.
- The pulse gas system was tested. A tendency for the nitrogen regulating valve to plug with small particles of dust and act erratically was corrected by adding a high pressure gas filter upstream of the valve.
- A test of the purging system indicated that at least 10 seconds is required between each solenoid firing to allow the pressure in the reservoir to return to the desired purge pressure. The Furnas controller was reprogrammed accordingly.

- Fourteen filter elements which were cast in Hastelloy-X cups were installed in the filter vessel and the cups were edge welded to the sleeves on the tubesheet.
- A 3 hour candle filter test was conducted. The operation of the filters proceeded as expected with the candles successfully pulse cleaned of dust. The face velocity varied between 6.0 and 9.4 fpm during operation on coal and the estimated dust loading was 2400 ppmw of sorbent.
- The particulate sampling system for the candle filters was successfully tested.
- A particulate collection efficiency of 99.92% for candle filters was measured during the test of the particulate sampling system.
- Ceramic coupon samples provided by John Sawyer were installed in the filter vessel and were encased in a cage constructed of expanded RA-330.
- Installed additional ceramic coupon samples from Refractron.
- Two candle filters were discovered to have broken due to a 4.7 earthquake. The two broken candles were replaced.
- A extended filter test was run during May. Two more candles failed at some point during the run. Collection efficiencies were measured to be above 90% but never approached the 99.9% that is expected with these candles.
- A sample of a Nextel 440 bag was placed in a furnace heated to 1900°F and exposed for 24 hours. No readily observable changes occurred and the weight change (loss) was negligible.

4.2 DISCUSSION

4.2.1 Primary Cleanup Device

Development work on the Particulate Rejection Impact Separator (PRIS) has proceeded through subscale testing and flow visualization modeling. The full scale PRIS design has been defined based on results from these development tools. The PRIS concept being developed is to use a series of rows of staggered ceramic rods. Each row creates jets of ash laden gas that impinge on the next row of rods downstream, inertially separating the ash from the gas.

Subscale PRIS Testing

Subscale testing of a rod type PRIS insert has been on-going. The PRIS design is illustrated in Figure 33. The design features seventeen alpha-sintered silicon carbide tubes mounted in six staggered rows. The 1.25 in. O.D. by 0.75 in. I.D. eight inch long tubes were supplied by Carborundum and are marketed as Hexoloy SA silicon carbide. The tubes are mounted in a refractory insert with a rectangular flow passage.

P00-017

Figure 33. Subscale Rod Matrix PRIS Concept

The PRIS insert has been exposed to CWM exhausts in IBSTF Test Nos. 4 to 9 in this reporting period. Key operating conditions and test results are summarized in Table 6. During this testing the PRIS has been exposed to combustion gases for 97.9 hours of which 21.5 hours were logged burning 12,171 lbs of CWM. This brings totals for all testing with this rod insert up to 117.9 hours of combustion of which 28.5 hours were burning 14,689 lbs of CWM.

The PRIS has seen temperatures of 2900° to 3000°F on the inlet side and 2669°F on average on the outlet side. The outlet PRIS temperatures recorded in IBSTF Test No. 9 are also included in Figure 32. The PRIS has consistently operated with a pressure drop ratio of 1.0 to 1.4%.

PRIS ash/slag removal performance is documented in Table 6. In this table the ash removal is reported based on particulate measurements made downstream of the PRIS and secondary combustor. This measurement of up to 98% removal is the ash/ slag removed from both the

primary combustor and the PRIS. In Test No. 8, taking into account the measured primary slag capture efficiency of 61%, the PRIS demonstrated a slag capture of 95%. The design goal for the PRIS is to demonstrate ash removal efficiencies above 70% of the ash entering the PRIS. Clearly, these subscale results indicate that the PRIS is performing far above goal.

Post test inspection of the PRIS is documented by photographs included in Figures 34 to 38. The PRIS as it was originally installed is shown on the outlet side in Figure 34. Compared to those photos the pictures of the inlet and outlet sides in Figures 35 and 36 after IBSTF No. 7 with 13.6 hours of CWM combustion. The rods are in good shape with only one crack noticeable on the left most front rod in Figure 35. Inspection with a borescope also indicated that rods in row 3 were slightly damaged. The back rods have a "glassy" coating and a light accumulation of slag. The rods on both inlet and outlet sides are free of heavy slag deposits that would indicate a potential blocking problem. On the outlet side slag flow is seen towards the slag tap. The slag freezes around the slag tap indicating the temperatures in this region are too low. The refractory insert body shows several large cracks, particularly on the inlet side.

The results after Test No. 7 indicated superior PRIS performance. Damage to the rods and refractory was believed to be a function of the mechanical design of mounting the rods fixed at both ends in the insert and the rectangular geometry. After Test No.9 the problem was found to be more severe. In Figures 37 and 38 are photos of the inlet and outlet sides of the PRIS taken after Test No. 9. At this point the PRIS has been exposed to 28.5 hours of CWM combustion. Damage was observed to almost all the rods. Cracks in the refractory have grown considerably, with little doubt that added stresses were put on the rods. Most of the rods show a loss of material, which at this point before the failure analysis is complete is attributed to hot corrosive attack by alkali in the slag. The only rods intact are located in the lower velocity region of the row nearest the outlet side. These rods are covered with a thick glassy coating.

Figure 34. Outlet Side of Rod Insert at Initial Installation

Figure 35. Rod Insert Inlet Post Test Inspection

The photos do indicate that the PRIS continued to remove slag in spite of the damage. Slag accumulations in between the rods are light and slag flow is seen out of the PRIS towards the slag tap hole. Again the slag froze surrounding the slag tap hole. The outlet of the PRIS vessel and the secondary combustor continue to be free of slag.

In conclusion, subscale testing of a rod type PRIS indicates excellent ash removal efficiencies of up to 95%. The PRIS rods have suffered substantial damage due to the mechanical attachment

Figure 36. Rod Insert Outlet Side - Post Test Inspection

design and hot corrosion. New designs for attaching the rods are discussed in following sections. Alternative rod materials are available and will be selected following the failure analysis of the silicon carbide rods. As a backup to the silicon carbide rods another subscale insert was fabricated containing solid rods of high purity alumina. Alumina rods are highly resistant to erosion and corrosion, but more susceptible to thermal stresses than silicon carbide. This insert will be installed in the IBSTF for the next test along with samples of other candidate materials.

Subscale Flow Visualization

After the first several IBSTF tests build-up of slag in between the rods appeared to be a problem. As a means of investigating the cause of this problem and gaining a better understanding of the PRIS operation a plexiglass flow visualization model was operated. The model was run injecting atomized honey into the PRIS inlet as shown in Figure 39.

The model is run for 2 hour periods of honey injection at a constant injection rate and a $\Delta P/P$ across the PRIS of 1%. Visually, most of the honey is captured in the first three rows of rods. The majority of the honey flows down the rods and flows along the bottom of the duct. Some shedding of relatively large honey ligaments is observed from row to successive rows. At the final row the gas velocity is reduced and only a very few ligaments are observed shedding into the

Figure 37. PRIS Inlet After Test No. 9

downstream PRIS chamber. These ligaments are not entrained with the gas flow, but fall depositing on the back wall.

The collection efficiency of the model is determined through a mass balance of the honey injected into the PRIS, the honey collected in the slag pit, and the honey collected in dual exhaust filters. The data indicate that the PRIS insert is capable of removing 99+% of the injected honey. The mean droplet size of the honey injected into the PRIS is determined with a line of sight particle size analyzer. The measured SMD is 41 microns.

The model has been exercised using this procedure to investigate modifications to the PRIS outlet and the angle of PRIS tilt. The PRIS outlet has been modified to increase the exit velocity from 27 to 300 fps. On testing the honey collection efficiency was still better than 99%. However, a far larger portion of the honey was sprayed on the back wall of the PRIS outlet from the shedding described above. The PRIS tilt angle was increased from 30 to 60°. The only difference this caused was for some honey entrainment off the back edge of the PRIS insert. The collection efficiency still remained in excess of 99%.

Figure 38. PRIS Outlet After Test No. 9

Figure 39. Subscale Flow Visualization With Honey Injection of Rod Type PRIS

Full Scale Design

Based on the results of the recent subscale PRIS results, the full scale PRIS has been designed. A primary design goal has been to lessen the occurrence of thermal stresses that are believed to be part of the cause of silicon carbide rod and refractory failures in the subscale PRIS. The design for the spool section containing the rods is shown in Figure 40. The design illustrated in the figure shows 60 ceramic solid rods mounted perpendicular to a circular flow duct. The ceramic material used for the rods will be determined based on future subscale PRIS tests. The duct has a 15 in. inlet and a 21 in. outlet diameter. The gas velocity through the first row of rods will reach 290 ft/s and the velocity through the last row will be 150 ft/s. The total pressure loss through the rods will be 1.32%. The 1.25 in. rods are spaced 0.75 in. apart with a 2 in. spacing from row to row.

Figure 40. Full-Scale PRIS Design in Circular Duct Geometry

The flow path has been changed from a square to circular duct geometry to lessen stress concentrations that develop in the corners of the refractory. The rods are shown to be fixed rigidly in only one end. The bottom end of the rods are cast into the refractory, while the top ends slip through oversized holes through the upper refractory. The design is intended to allow the rods to thermally expand in one direction so that mechanical stresses will not develop. The mounting of the PRIS rods in the refractory has been studied to determine the most cost effective approach. As seen from the illustration in Figure 40 the holes that penetrate the refractory in the top are very close with refractory thicknesses between holes as small as 0.625 inch. The rods have a 1/16 in. gap to the refractory as they are positioned in the holes.

Manufacture of this assembly is not going to be easy. The approach that is being considered and has been used in making the full scale flow visualization model is to use "machinable wax" to create the core and hold the rods in place for casting. The wax piece will be drilled and the rods fitted through. The top end of the rods will be wrapped with tape to a 1/16 in. thickness. This whole assembly will be placed in a mold and the refractory will be poured and set to create the refractory shape. The wax will be melted out and the tape burned out to free the top end of the rods.

A detailed drawing of the full scale PRIS design is included in Figure 41. The rod insert is seen at the top of a vessel with constant flow passage diameter. The rod insert is attached as a removable spool. The PRIS is oriented at 45° from normal gravity. The PRIS is insulated with three layers of refractory materials as was the full scale combustor to minimize heat loss. The slag is collected at the bottom of the exit end of the PRIS through a slag tap that connects to a removable batch slag pit. The exhaust gas flows through a passage directly above the slag tap hole.

In order to aid in the PRIS design a full scale flow visualization model has been fabricated. The model, shown in Figure 41, has not been operated yet, but should provide valuable information into the aerodynamic flow pattern and slag flow characteristics of the PRIS. The design will be studied using helium bubbles to trace the aerodynamic streamlines and honey to simulate the slag capture and flow.

4.2.2 Post-Secondary Systems

Much of the work focused on installation and debugging of the Integrated Bench Scale Test Facility and examination of virgin candles. Acurex Corporation, which has been under subcontract, conducted XRD, SEM/EDX and four-point bend testing on unused candles that was reported in March 1989. Some additional testing done at Solar within the last year is reported here.

Candle Testing

Two Schumacher dia-Schumalith candle filters were examined by Solar and are denoted here as 5A and 5B. Filter number 5A was examined in several locations including areas of the matrix, individual fibers and an inclusion that appeared on the outer surface. A transverse section (#5B) was also examined. In most cases, the major elements were found to be silicon and aluminum. These two elements were present in all but one EDX spectra.

Figure 41. Cross-Section of Rod Insert for Full-Scale PRIS

An electron micrograph of the outer diameter surface of the candle is shown in Figure 42. A number of individual fibers and inclusions can be seen in addition to the matrix. A closer view of the top center is shown in Figure 43. An inclusion can be seen as the dark object at the bottom center of the second micrograph (it can also be seen in the first micrograph but is quite a bit smaller). An EDX spectrum was taken of this individual inclusion and is shown in Figure 44. The presence of the elements silicon, aluminum, calcium, iron, sodium, sulfur, and chlorine was verified by EDX.

Also evident in Figures 42 and 43 are fibers. A fiber located slightly above and left of the inclusion just mentioned was examined by EDX which revealed the presence of silicon and aluminum. The spectrum is shown in Figure 45.

A transverse view of a candle is shown in Figure 46. This view shows the coarse grain structure of the inside part of the candle as well as the thin outer layer which has a finer pore structure. This inner area is present mainly to impart strength to the candle. The thin, outer layer shown at the top of this micrograph is responsible for the filtration. This two layered approach reduces the pressure drop during filtration while maintaining candle strength and high collection efficiencies. An EDX spectrum, shown in Figure 47, was taken of a fiber located in the outer layer of the candle. This fiber can be seen in the upper left section of Figure 47 about 1.5 inches from the left edge and about one-half of an inch down from the surface. The spectrum of this particular fiber contained only silicon and aluminum.

Figure 42. Outer Diameter Surface of the Candle

Figure 43. Expanded View of Outer Diameter Surface

Figure 44. EDX Spectrum of Inclusion

Figure 45. EDX of Candle Filter #5A Fiber

Figure 46. Transverse View of Candle

Figure 47. EDX Spectrum of Fiber Located in the Outer Layer of the Candle

A summary of the EDX results taken from two candles is shown in Table 7. In all cases, silicon was detected. Aluminum was seen in all spectra save one. In this case, only silicon was detected indicative of a pure grain of silicon or silicon carbide. EDX will only detect elements having molecular weights equal to or greater than that of sodium. Thus, carbon is not detected even though it is obviously present in the silicon carbide grains.

The same tests will be repeated on candles that have been exposed for 50 hours. This testing will be done at both Solar and Acurex Corporation and should verify whether candles are being markedly altered as a result of exposure to typical DCFT conditions.

Table 7. Energy Dispersive X-ray Analysis of Two SIC Candle Filters

Candle Location	Elements Detected
Candle 5A - O.D. Surface	
overall	Ca, Fe, Al, Si, Cl, K
fiber	Fe, Al, Si, K
fiber	Ca, Fe, Al, Si, S, Cl, K
substrate	Fe, Al, Si, K
outer surface	Al, Si, S, Cl, K
matrix	Al, Si, K
fiber	Al, Si
inclusion	Ca, Fe, Na, Al, Si, S, Cl, K
Candle 5B - Transverse Section	
fiber	Al, Si
overall	Fe, Al, Si, K
overall	Ca, Fe, Al, Si, Cl, K
inclusion	Ca, Fe, Cu, Na, Al, Si, S, Cl, K
grain	Si
fiber	Al, Si

Full-Scale Design

Preliminary design work was completed on a full-scale candle system. Some of the design criteria are listed in Table 8. Basically the design includes a cooled-tubesheet, a face velocity of 12 fpm at full load and two filter vessels approximately 12-ft in diameter.

The large volume of fly ash generated makes a continuous ash removal system necessary. One system concept includes a water-cooled screw-conveyor to transport the flyash to lockhoppers and to lower its temperature at least 600°F from 1850°F. Once at 600°F, the material can be removed using lock-hoppers.

System Tests

A number of system shake-down tests were run without candles in the vessel. This included PRIS tests as well as overall system performance tests. During one of these tests, a leak developed in the water-cooled tubesheet. A serpentine water channel, which was milled into the disk of type 316 stainless steel, was sealed with 316 stainless cover plates which were furnace braced into the tubesheet. It appears that the braze job was not satisfactory due to incomplete penetration of the brazing compound into the gap between the plates and tubesheet. Rather than brazing this again, new plates were welded over the channels.

Table 8. Design Information for the Secondary Particulate Removal System

Condition	Value
Temperature	1850°F
Pressure	150 psia
Face Velocity	12 fpm
Dust Loading	6000 ppmw (max)
Candle Dimensions	
O.D.	60 mm
Length	1.5 m
Bulk Density of Fly Ash	45 lbs/cuft

Twenty candles were cast using a method similar to Solar's ceramic recuperator technology. These candles were cast into Hastelloy-X cups which were then edge welded to Hastelloy-X sleeves which were already welded directly to the tubesheet.

Testing and debugging of the purge system revealed that firing of the four solenoids one after another resulted in very low pressure pulse gas for the third and fourth solenoids. The Furnas controller was reprogrammed to allow a 10 second interval between successive solenoids to allow the pressure to build up to its desired setpoint. Thus, a purge cycle is complete in about 35 seconds. All solenoids and ball valves were verified to be functioning correctly.

A high pressure filter housing and element was installed upstream of the nitrogen purge gas regulator. There had been some problems with dirt and condensation affecting the regulator performance. The problems did not recur following installation of the filter.

Three runs were performed with the candles in place. Two of these runs were with coal whereas one run was with diesel fuel #2 and injected dolomite.

A three hour experimental run was conducted with the candles in operation. This particular run was essentially a preliminary test of the candle system prior to the planned 50 hour test. No particulate sampling was performed for this run. The candles were operated at a face velocity that ranged from 6.0 to 9.4 fpm for the duration of the run. The temperatures at various locations in the filter vessel rose steadily during the run from 1323°F at the filter vessel inlet at the beginning of the coal run to 1771°F close to the end. The gas temperature dropped steadily as it passed through the vessel. For example, the temperature at the flow nozzle at the beginning of the run was only 803°F but by the end of the run it increased to 1280°F. The temperature in the filter vessel, however, ranged from 977°F at run beginning to 1570°F by the end of the run.

The dust loading was estimated at 2400 ppmw of sorbent plus any additional particulate matter from the coal slurry and from the air supply. An analysis of the dust is forthcoming. A visual inspection of the candles following the run revealed all fourteen intact and relatively clean of dust. The filter vessel was opened at the conclusion of the run and 7.7 lbs of dust were collected from the bottom of the vessel. Visual inspection of the candles revealed a small amount of dust was

still attached at the lower end of each candle. A higher purge pressure might have been more effective at removing this bottom portion of dust. The nitrogen supply was set at 200 psig which 120 psi above the pressure in the secondary filter vessel.

The prime data collected from this run is the differential pressure versus time curve, which was collected via computer. This data is represented graphically in Figure 48. Although not shown on the graph, the differential pressure during heat up on diesel was negligible and showed no change for the heat-up period. Once on coal, however, the differential pressure showed a steady increase over time. This is primarily the result of sorbent being introduced for sulfur dioxide control. One purging cycle was triggered at the end of the run. At this point, the differential pressure reached 1.6 psid, which was below the predetermined setpoint of 3 psid. The candles were effectively purged in 30 seconds and this is seen in the graph as the sharp decline in the differential pressure at the three hour mark.

Although the conditions of this test changed throughout as the system heated up, the ranges of various parameters are listed in Table 9.

Table 9. Candle Filter Operating Parameters During Shakedown Test

Parameter	Range
Face Velocity, fpm	6.0 - 9.4
Filter Vessel Temperature, °F	975 - 1570
Pressure, psia	95
Differential Pressure, psid	0 - 1.9
Dust Loading (est.), ppmw	2400

A second test was performed in which diesel fuel #2 was burned and dolomite was injected. The purpose of this test was to verify the particulate sampling system, the injection of diesel at the secondary for faster system heat-up, and verification of the load cell operation of the sorbent feed system.

The particulate sampling system was installed and tested. This system is comprised of two isokinetic sampling probes to measure the dust loadings upstream and downstream of the candle filters. The particulate collection efficiency will be calculated from these measurements. Each sampling station is equipped with two Balston absolute filters. During a run, only one filter is on-line. This permits an easy change of filters and data can be collected throughout the run.

During the test, diesel fuel was burned and dolomite was injected at the secondary zone. Sampling time for the upstream port was five minutes while the cleaner, downstream port was sampled for about one hour. From this test, a particulate collection efficiency of 99.92% was calculated. This indicates that the filters were effectively cleaning the gas and the candle attachment method was functioning properly.

Figure 48. Differential Pressure Versus Time Curve for Candle Filters

A few days later, the vessel was opened to remove the collected dust and to install ceramic coupon samples obtained from Refractron. Two of the fourteen candles were observed to have failed. It is suspected that an earthquake measuring 4.7, which struck San Diego the previous night, was responsible for the damage. The candles were known to be intact a few days prior. Since the two candles were adjacent, it is possible one candle broke and upon falling, it struck the other causing it to break. The candles were replaced within a few days.

Both candles broke at nearly the same place, one within 5.5 inches of the top of the candle and the other within 5.6 inches of the top. It is noteworthy that two candles from the Hot End rig have broken in the same location, i.e, within 6 inches of the top of the candle. Neither of the candles from the hot end broke during operation. In one case, the candle broke without an applied stress after it had been removed from the vessel. In the second case, the candle broke as the filter vessel was being opened. In this latter case, there was no stress on the candle at the exact moment of breakage, but it did occur moments after the vessel was being handled.

Several ceramic coupon samples were installed in the filter vessel for exposure to a DCFT environment. The coupons were suspended from RA-330 rod which was enclosed in an RA-330 expanded metal cage. This arrangement ensures that the samples are not lost in the event they should dislodge from the rods. Four additional coupon samples were received from Refractron of Newark, New York. These coupons were installed in a supplementary cage and installed in the vessel. Upon exposure to the gas stream for approximately 100 hours, they will be removed and sent to John Sawyer at Acurex for testing.

A third test was conducted to test the candles for 50 hrs. Average conditions for the candle filters are shown in Table 10. While these represent typical operating conditions, there were no transients of face velocity or differential pressure, and there were no temperature excursions. There were three occasions when the flow was switched from CWM to diesel #2. During these unplanned shutdowns, the flow through the filter vessel was diverted so that the candles did not see any sudden changes of temperature during the transitions. Two of the fourteen candles failed at some point during the run. It is not clear the exact point of failure. During the initial stages of the run, diesel fuel was burned and initially the differential pressure across the tubesheet gradually increased to as high as 2 psid. Some particulate from the air supply was probably contributing to this increase. During the first several hours, the differential pressure fluctuated between 1 and 2 psid, but fell to a relatively constant 0.5 psid after seven hours on diesel. It is possible one or both candles failed at this point, but this is not conclusive. At no point during the run did the pressure drop decline to near zero. Upon switching to CWM on Saturday morning, no increase in differential pressure was observed. Therefore, the differential pressure versus time curve did not show the characteristic saw toothed behavior. Inasmuch as the pressure drop did not increase to a 2-3 psid setpoint, it was not necessary to purge the candles. One purge cycle was initiated anyway and while a brief spike was seen with each solenoid firing, the pressure drop after purging was essentially unchanged.

Table 10. Candle Filter Operating Parameters.

Parameter	Range
Face Velocity, fpm	8.0 - 13.4
Maximum Temperature, °F	1846
Pressure, psia	95
Differential Pressure, psid	0 - 1.0
Dust Loading, (est.), ppmw	1100

Dolomite was being fed into the system at a rate which varied between 5-10 lbs/hr. Particulate samples were taken at various times, while on coal slurry, to determine loadings upstream and downstream of the candle filters. The sampling was performed isokinetically and the particulate was trapped using Balston absolute filters. Particulate samples showed a marked decrease in particulate downstream of the filters, thus there was no obvious indication of failed candles. The particulate data are shown in Table 11. Collection efficiencies averaged around 90% but did not approach the 99.9% generally expected for candles. However, it also appears that the collection efficiency declined during the run. When the flow nozzle was removed from the top of the filter vessel, a deposit of dust was seen just upstream of the nozzle, indicating that dust was passing through tubesheet. These deposits would of course effect the calculated collection efficiencies to some degree.

Although the filter vessel has not yet been opened to remove the failed candles, it appears that all candle failures are occurring in the same location, i.e. approximately 6 inches from the top portion of the candle about 5.5 inches from the top. At this location in the candle, there is a

Table 11. Particulate Collection Efficiency Data for Test 09.

Sample	Sample Times	ppmw	Collection Eff., %
downstream	3:55 - 4:25	51	
upstream	3:58 - 4:08	681	92.4
downstream	6:42 - 7:42	110	83.8 ^a
downstream	8:03 - 9:03	149	
upstream	8:31 - 8:41	2961	94.2
downstream	9:36 - 11:06	46	
upstream	10:45 - 10:55	732	94.5
upstream	14:52 - 15:07	1133	84.9
downstream	13:34 - 14:50	161	
^a collection efficiency based on upstream data from 3:58 - 4:08.			

transition from a dense to a less dense region which is readily seen on the inside of the candle. While the location of breakage of these two candles has not yet been measured, observation using a borescope revealed that the candles broke near the top once again.

Max Müller of Schumacher visited San Diego on May 29th to discuss the candle failures. Mr. Müller believed the candles should not have failed under the conditions they were exposed. The possibility of a manufacturing flaw has not been ruled out at this time.

Solar's mounting method differs from that used by Schumacher and by Industrial Filter and Pump. Schumacher prefers a gravity based system where weights of some kind are placed on the candle. Industrial uses a pin and gasketing arrangement. Solar has used a refractory bonding method where the candle is cast in a Hastelloy-X cup which is edge welded to a sleeve located on the top of the tubesheet. Solar's mounting system is perhaps the most rigid of the three, permitting little lateral movement of the candle. Alternate mounting methods are being considered. It is noteworthy, however, that the present mounting method provides a perfect seal and candles can be replaced easily and quickly with the cup and sleeve arrangement.

The Dia-Schumalith candles that have been used to date at Solar were also used at the EPRI-sponsored Grimethorpe test. Many candles in that test survived up to eight hundred hours. The salient differences between Solar's system and the Grimethorpe system, aside from the system conditions, are the candle attachment method and the tubesheet design. A cooled tubesheet is employed in this design primarily because of the higher temperatures. At Grimethorpe, the tubesheet was constructed from RA-333 and was uncooled. At Grimethorpe, weights were used to keep the candles attached to the tubesheet. Unfortunately, sufficiently large differential pressure excursions occurred, causing the weights to lift off and candles to bounce. This probable led to failure in some of the elements. Solar's design is more rigid and the candles themselves are cast in a refractory bond. Any flexibility at the free end of the candle would not

permit the candle to flex and might induce breakage. The advantage of this method is the candles cannot bounce from differential pressure excursions and the seal is very tight. Discussions with Industrial's Jim Zievers and Paul Eggerstedt revealed they used a similar method at one time. They abandoned this method because it was difficult to remove filters. Because of Soiar's cup and sleeve method, removal and installation is not a difficult procedure.

An alternate method is one employed by Industrial Filter and Pump. John Sawyer suggested we adopt Industrial's mounting method, basically to eliminate one more variable.

Discussions were held regarding the breakages with Max Müller of Schumacher, John Sawyer of Acurex, and Jim Zievers of Industrial Filter and Pump. The broken candles were extensively photographed. One of the Hastelloy-X cups with the remaining part of the candle has being sent to Acurex for inspection.

Tubesheet Performance

A water-cooled tubesheet of 316 stainless has been employed to suspend the candles. Temperatures were recorded for the tubesheet upstream and downstream surfaces, the gas in the filter vessel, the gas in the downstream plenum and the inlet and outlet cooling water. The flow rate of the water was also measured and recorded. The temperature loss in the gas passing through the filter vessel is due to the heat losses to the cooling water as well as other heat losses through the walls of the vessel.

Basically, heat flux to the water was independent of the water flow rate in the range of 4.2 to 10.4 gpm. The flux to the water was generally about 79,000 Btu/hr. At this flux, and with the gas flows that were recorded through the filter vessel, an average temperature loss due to water cooling was calculated to be about 105°F. Data were recorded at thirty minute intervals for the duration of the run. Seven data points shown in Table 12 are representative.

Table 12. Data for Water-Cooled Tubesheet for Run No. 9

Date/Time	Water flow rate (gpm)	DT _{water} (°F)	Q _{water} (Btu/hr)	ΔT_{gas} (°F)	
				Calculated	Measured
10 May 21:10	10.4	14.5	72,384	93	254
11 May 7:39	10.4	15.2	75,878	105	165
11 May 15:38	6.0	7.6	79,488	97	258
12 May 4:42	6.0	28.7	82,656	110	241
12 May 7:07	6.0	27.6	79,488	117	243
12 May 10:12	6.0	29.5	84,960	112	257
12 May 14:12	4.2	38.5	77,616	102	219

Heat losses were greater than expected.

The water cooling is keeping the tubesheet temperatures low. In general, the downstream tubesheet surfaces range from about 163 to 557°F and the upstream (cooling side) temperatures ranged from about 264 to 528°F. Some of the twenty-two thermocouples have failed. Two other thermocouples are providing somewhat higher values (677 and 990°F, for example) but these might have detached from the tubesheet. Their location is near the cooling channels, not at the perimeter where higher readings might be expected.

Alternative tubesheet cooling methods are being explored to reduce the heat removed from the tubesheet. These include using heat transfer fluids such as Dowtherm or cooling with air. Still another alternative is using an uncooled tubesheet constructed from a high temperature alloy.

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

5.1 SPECIFIC ITEMS OF PROGRESS

- The slurry properties, tested in the TSSC and IBSTF, were reviewed and characterized for the development of target fuel specification:
 - Majorities of testing fuels were formulated from eastern Kentucky coals (e.g., Kentucky 4A, 5, Elkhorn, Blue Gem) except that a Pittsburgh-seam Powhatan coal was used for sorbent injection runs.
 - Loadings of 50 to 60 wt% with ash of 2.3-5.5% (on dry coal basis) and particle top size of 45 μm with mean size of 10 μm were used in the formulation of slurries.
 - Alkali concentrations were ranged from 82 to 978 ppm and sulfur content up to 3.26 wt% has been used in the sorbent injection testing.
 - Ash fluid fusion temperatures (under reducing conditions) were kept below 2700°F in most runs with high slag retention.
- Slurries formulated without stabilizer were encouraged for the hot-end rig combustion tests resulting in no gummy deposits in the feed-line strainers.
- In an attempt of mixing sorbent with coal-water slurry, the results indicated below 2% of sulfur being retained with the primary-zone slag.
- Primary-zone slag from the subscale two-stage combustor runs showed considerable dilution by dissolved refractory.
- Characterization of slag viscosity from burning Batch G which was formulated by Powhatan coal with sorbent additive indicated the low slag viscosity could contribute the results of low slag retention.
- Magnetite and lime have been used for adjusting the ash fusion temperatures of CWM fuels, and hydrated alumina has been used for modifying the ash slag viscosity.
- Coal alkali in CWM was reviewed with considering alkali removal via coal cleaning, slag retention, particulate removal and other alternatives. We observed:
 - Equivalent amounts of 62.2% alkali from raw coal could be removed through heavy media separation and a total of 80.9% of the original alkali could be removed with an addition of advanced cleaning.
 - Vapor-phase alkali concentrations from burning CWM after combustion island and secondary cleanup were estimated in the range of 30 to 80 ppb.
 - Alkali sulfate compounds were found in the exhaust particulate samples confirming vaporized alkalis tied with fly ash and spent sorbent.

- Analyses of alkali concentration indicated dolomite and hydrated lime sulfur sorbents containing only trace amounts of alkali.
- Coal source studies found that Utah's Soldier Creek bituminous coal appears to be an acceptable source coal for the Western U.S. market area.
- Correlation was developed using column flotation test results for processing Kentucky 4A and Illinois No. 6 coals. The results showed
 - The most important operating variable found to impact column performance was the amount of wash water sprayed on the froth column.
 - Variations in the frother dosage, aeration rate, solid loading, froth depth, and particle size were also found to affect the flotation rate.
- A series of combustion test fuels were formulated with important fuel characteristics to improve combustor performance and to develop target fuel specification.
- Fuel costs were updated and projected on various requirement scenarios and on supplying fuels to a coal-fueled Centaur Type H gas turbine cogeneration system.
- The feasibility of assembling an on-site integrated fuel preparation facilities has been studied for preparing and burning fuel directly with reduction or elimination of the need for additives.

5.2 DISCUSSION

5.2.1 Coal Fuel Specifications

Fuel Specification

Slurries from different batches supplied by AMAX have been tested in the subscale combustor and the integrated bench scale facility. Table 13 summarizes the property ranges of coal-water slurry fuels which have been tested at Solar. Majorities of slurry fuels used for combustor testing were formulated from eastern Kentucky coals (e.g., Kentucky 4A, 5, Elkhorn, and Blue Gem coals), except that a Pittsburgh-seam Powhatan coal has been used in the sorbent injection runs. The loading of 50 to 60 wt% of coal with ash of 2.3 to 5.5% was used in the formation of slurries. The top particle size in slurries of recent runs has been reduced to 45 μm for improving the slag retention. The slurry viscosity was maintained around 200-300 cp @ 100 sec^{-1} with emphasis on lowering the amount of stabilizer used. The sulfur content varied from 0.56 to 3.26% (dry coal basis) has been used for sorbent injection testing. The alkali content in the coal ash basis was ranged from 0.30% to 2.6% of Na_2O and 0.31% to 2.7% of K_2O , respectively. This is corresponding to about 82 to 978 ppm of total alkali content in the slurry feed. Ash fluid fusion temperatures (under reducing conditions) were kept below 2700°F in most satisfied slag-retention runs.

Table 13. Ranges of CWM Fuel Properties Tested at Solar

Slurry Loading	49.8-60.6 wt%
Ash Content (Coal Basis)	2.3-5.5 wt%
Particle Size	
Top Size	45-100 μm
Mean Size	7.5-21 μm
Slurry Viscosity (100 sec ⁻¹)	150-470 cp
Slurry Heating Value (LHV)	6190-7801 Btu/lb
Volatile Matter (Coal Basis)	31.7-38.8 wt%
Sulfur Content (Coal Basis)	0.43-3.26 wt%
Nitrogen Content (Coal Basis)	1.02-2.19 wt%
Alkali Content (Coal Ash Basis)	
Na ₂ O	0.3-2.6 wt%
K ₂ O	0.3-2.7 wt%
Ash Fluid Fusion Temperature	
Reducing	2315-2700+°F
Oxidizing	2518-2700+°F

In an attempt to eliminate clumps of gelled residual slurries observed in the fuel line strainers during the hot-end rig testing, slurries with improved rheological properties were prepared. Two batches of slurries were formulated without Flocon stabilizer. (Pfizer's Flocon, a liquid form of xantham gum, was used usually as a stabilizer for coal-water slurry at a concentration of about 0.01-0.05 wt% range.) Batch Q and R made without stabilizer were formulated using Kentucky 4A coal. Detailed analyses of their compositions and slurry properties are listed in Appendix A. Batch Q contained 51.0 wt% coal and has a particle top size of 45 μm and the mean size of 12.6 μm . The measured viscosity of Batch Q showed a desired pseudo-plastic rheological behavior, a decreasing viscosity with an increasing shear rate. However, the determined ash fusion temperatures were well above 2700°F. Batch R contained 54.3% coal and had a particle top size of 45 μm with a mean size of 10.4 μm . A small amount of lime additive has been used to reduce ash fusion temperatures within the range of 2400-2650°F (under reducing atmosphere) to meet the fuel specification. The measured viscosity of Batch R showed a slightly dilatant behavior, an increasing viscosity with an increasing shear rate. Also an easy settling and relatively difficulty re-agitation were observed. However, the slurry showed no gummy material deposits found in the system line strainers during the hot-end rig combustion testing. The slurry without stabilizer is encouraged for the hot-end rig testing which equipped with a small injector.

In addition, two batches of high-sulfur slurry fuels (Batches F and G) formulated with Powhatan coal were tested for sorbent injection and for sulfur capture with lime additive. Appendix A of Batches F and G presents detailed analyses of both slurries. The feed coal has a high sulfur (3.13%) and iron (Fe₂O₃, 20.9%) contents mainly due to the high pyrite content. As shown in the

table, Batch F has a high coal loading of 60.6% with an ash content of 3.4% in the slurry. A relatively narrow range of ash fusion temperatures between initial deformation and fluid temperatures were observed in both oxidizing and reducing atmospheres. Batch G, with the lime additive, has an initial deformation temperature (under reducing atmosphere) at only about 2000°F. The lime addition in Batch G was about 5.3 wt% on a slurry feed basis or corresponding to about 0.8 of Ca/S ratio. In the combustion results, a high retention of slag (84.4%) was obtained in TSSC tests (Runs 34 and 35) using Batch F compared to the slag retention of 46.4% in Run 36 using Batch G fuel. It is uncertain whether the coal loading in the slurry has a definite impact on the slag retention. Slurries with higher coal loadings increase fuel heating value per unit volume. Consideration is being given to investigate high levels of coal solid concentrations on the fuel combustion performance test.

Slag Composition and Characterization

Properties of combustor slag samples obtained from TSSC tests on burning Batches S-1 and S-2 are analyzed and listed in Tables 14 and 15. Analyses of particulates obtained from a water-cooled gaseous sampling probe are also listed in the tables along with the soluble metals found in the water samples. Batches S-1 and S-2 were parts of combustion performance testing fuels used to determine the important fuel characteristics in terms of combustor performance. In the combustion results, the slag capture for Batch S-1 run was 68.9% (on coal ash basis), but it dropped to only 34% for the run using Batch S-2.

Batch S-2 was the slurry prepared without stabilizer. As described previously, slurries prepared without stabilizer (Batches Q and R) showed no gummy deposits in the strainers during the hot-end rig combustor testing. And they were recommended for the hot-end rig testing which equipped with a small injector. However, Batch S-2 slurry (without stabilizer) did not burn as smoothly in the TSSC combustor as the S-1 fuel did. Slurry without stabilizer has also been tested by workers at Sandia Labs. They observed an improvement of fuel atomization properties due to less particle agglomeration. Here, the observation from the test on slag capture showed the opposite results. Coal particle settlement and/or segregation could contribute parts of the reasons.

Analyses of slag composition and characterization indicate that some char had mixed with the primary-zone slag in Batch S-1 run (as shown in Table 14 with a higher carbon content). However, the secondary zone slag of S-1 run as well as the primary-zone slag of S-2 run (Table 15) contained very low in carbons, as one would expect with efficiency combustion. From the analyses of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios, it appears that the primary zone slag was diluted by dissolved refractory. The indicated dilution (Based upon the Fe_2O_3 analyses) of 0.34 part refractory per 1 part slag was estimated for the Batch S-1 primary-zone slag. It also appears from the CaO and MgO analyses that the Batch S-1 slag samples was diluted by residual sorbent contamination. On the contrary, as shown by the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and Fe_2O_3 analyses as well as the CaO and MgO analyses in Table 15, S-2 slag samples did not appear to be as much dilution of the slag by refractory or sorbent contamination during the run. The particulate samples collected from both S-1 and S-2 runs (Tables 14 and 15) contained about 15-18% carbon and were enriched in iron.

Table 14. Properties of Combustion Products from TSSC Run 43 (Burning S-1 Fuel)

	Coal Ash in S-1 Fuel	Primary Zone Slag	Secondary Zone Slag	Dust Collection	
				Particulates	Scrub Water, ppm
Ultimate Analysis, %					
Carbon		10.0	0.026	13.0	
Hydrogen					
Nitrogen					
Sulfur					
Oxygen					
Chlorine					
Ash		90.0*	99.9+*	82.0*	
Carbon-Free Ash/Slag Composition, %					
SiO ₂	46.58	27.80	32.82	32.48	12.5
Al ₂ O ₃	26.24	34.37	28.35	19.66	14.6
TiO ₂	1.06	0.74	0.92	1.00	0.3
Fe ₂ O ₃	12.12	9.03	9.94	21.94	28.0
CaO	3.99	10.17	11.69	4.45	30.9
MgO	0.50	5.10	6.18	2.44	14.5
SrO		0.13	0.19	0.15	0.2
Na ₂ O	1.29	0.85	0.939	0.96	3.0
K ₂ O	1.01	0.56	0.653	0.83	2.0
P ₂ O ₅	0.16	<0.01	<0.01	0.24	1.1
MnO ₂		0.04	0.06	0.11	1.0
PbO		<0.02	<0.02	<0.01	<1.0
V ₂ O ₅		0.04	0.03	0.05	0.1
SO ₃		0.67	0.12	0.76	297
Water Soluble Na ₂ O		0.021	0.020		
Water Soluble K ₂ O		0.007	0.005		
SiO ₂ /Al ₂ O ₃ Ratio	1.65	0.81	1.16	1.65	0.86
Base/Acid Ratio	0.25	0.41	0.47	0.58	2.86
pH					2.54
Dissolved Solids, ppm					389
Ash Fusion Temperatures, °F					
Reducing, Initial	2310	2357	2289		
Reducing, Softening	2375	2454	2328		
Reducing, Hemispherical	2424	2463	2365		
Reducing, Fluid	2687	2520	2425		
Oxidizing, Initial	2659	2494	2408		
Oxidizing, Softening	2668	2496	2419		
Oxidizing, Hemispherical	2700+	2506	2441		
Oxidizing, Fluid	2700+	2539	2524		
*By difference.					

Table 15. Properties of Combustion Products from TSSC Run 44 (Burning S-2 Fuel)

	Coal Ash in S-1 Fuel	Primary Zone Slag	Dust Collection	
			Particulates	Scrub Water, ppm
Ultimate Analysis, %				
Carbon		0.052	16.6	
Ash		99.9*	83.2*	
Carbon-Free Ash/Slag Composition, %				
SiO ₂	46.58	40.81	33.63	11.9
Al ₂ O ₃	28.24	31.67	16.37	22.1
TiO ₂	1.08	1.04	0.97	0.5
Fe ₂ O ₃	12.12	12.54	23.11	34.1
CaO	3.99	3.55	1.78	17.3
MgO	0.50	0.56	0.62	7.7
SrO		0.21	0.11	0.3
Na ₂ O	1.29	1.25	0.86	3.0
K ₂ O	1.01	0.999	0.73	2.0
P ₂ O ₅	0.16	<0.01	0.30	1.6
MnO ₂		0.04	0.11	0.8
PbO		<0.02	<0.01	<1.0
V ₂ O ₅		0.04	0.05	0.1
SO ₃		<0.01	0.79	347
Water Soluble Na ₂ O		0.007		
Water Soluble K ₂ O		0.005		
SiO ₂ /Al ₂ O ₃ Ratio	1.65	1.29	2.05	0.54
B ₂ O ₃ /Al ₂ O ₃ Ratio	0.25	0.26	0.53	1.66
pH				2.44
Dissolved Solids, ppm				400
Ash Fusion Temperatures, °F				
Reducing, Initial	2310	2325		
Reducing, Softening	2375	2377		
Reducing, Hemispherical	2424	2467		
Reducing, Fluid	2667	2686		
Oxidizing, Initial	2659	2589		
Oxidizing, Softening	2688	2630		
Oxidizing, Hemispherical	2700+	2700+		
Oxidizing, Fluid	2700+	2700+		
*By difference.				

Slag samples obtained from the combustion runs (TSSC Test Nos. 34, 35, & 36) burning slurry Batches F and G were also analyzed for their compositions and fusion temperature properties (as shown in Table 16). Batches F and G were formulated by Powhatan coal with higher sulfur contents. As reported, a high retention of slag was obtained from the Batch F runs. However, retention of the slag from Batch G fuel was poor, and the slag had a grainy, bubbly appearance. Obvious erosion of the high-alumina refractory occurred during combustion. A high content of Al₂O₃ was obtained in Batch F slag indicating a possible contamination of refractory in the sample. The high Al₂O₃ also results high ash-fusion fluid temperatures under either reducing or oxidizing atmosphere for the Batch F slag sample as compared to the parent coal ash.

Table 16. Coal Fuel Ash and Slag Properties

	Batch 'F' Ash	Batch 'F' Slag (Runs 34 & 35)	Batch 'G' Ash	Batch 'G' Slag (Run 36)
Composition, wt%				
SiO ₂	42.8	37.8	13.9	34.4
Al ₂ O ₃	22.8	39.5	7.6	27.8
TiO ₂	1.11	0.92	0.33	0.82
Fe ₂ O ₃	20.9	20.2	7.1	12.6
CaO	1.91	1.63	18.2	18.2
MgO	0.42	0.49	11.4	10.3
SrO	-	0.07	-	0.10
Na ₂ O	1.59	0.529	1.21	1.05
K ₂ O	1.30	0.825	0.49	0.465
P ₂ O ₅	0.03	0.06	0.04	0.06
MnO ₂	0.05	0.04	0.04	0.04
V ₂ O ₅	0.05	0.05	0.02	0.04
PbO	0.05	0.03	0.01	0.02
S (as SO ₂)	-	0.02	-	0.48
Carbon	-	0.12	-	1.88
Water-soluble Na ₂ O	-	0.051	-	0.012
Water-soluble K ₂ O	-	0.003	-	0.005
Base/Acid Ratio	0.377	0.279	1.76	0.659
SiO ₂ /Al ₂ O ₃	1.68	0.96	1.83	1.24
Fe ⁺³ /Fe ⁺² Ratio	-	0.04 ± 0.02	-	0.15 ± 0.03
Ash Fusion Temperature (°F)				
Reducing, Initial	2485	2267	2000	2153
Softening	2480	2364	2193	2168
Heml	2487	2455	2351	2187
Fluid	2495	2619	2440	2409
Oxidizing, Initial	2482	2682	2512	2323
Softening	2502	2700+	2544	2337
Heml	2516	2700+	2559	2367
Fluid	2518	2700+	2583	2474
T _{max} , °F (Graphical)		2570		2395
Reducing Atmosphere ASTM				
Fluid Temperature, °F		2619		2409
Viscosity, poise				
2500°F		>>1900		200
2700°F		>1900		67
Surface Tension, dynes/cm				
Adjusted to 2700°F		361		679

In the Batch G slag, high contents of CaO and MgO were due to the lime additive in the slurry. The fusion temperatures of Batch G slag sample have somewhat lower than those of their parent coal slurry ash, indicating a more homogeneous fluid parts of coal ash present in the slag. In addition, a total carbon of 1.88% was detected in the Batch G slag, showing some unburned char trapped with slag. Mossbauer data (Fe⁺³/Fe⁺² ratio of 0.15 for Batch G slag vs 0.04 for Batch F slag) also show that Run 36 (Batch G) was tested under much oxygen-rich conditions. Run 36 using fuel with 49.8% loading was tested at equivalence ratio of 1.08 instead of 1.30 in Runs 34 and 35 (Batch F runs). Although the sulfur content of the Batch G slag was 0.48% compared to

only 0.02% in the Batch F slag, the degree of sulfur retention in the Batch G slag (with lime additive) was below 2% on a total slurry sulfur basis.

Table 16 also shows a comparison of the available viscosity and surface tension data of slag samples. Viscosities of the slag from the Batch F and G were surprisingly high and low, respectively. The measurement of the Batch F slag viscosity was beyond the maximum allowable temperature restriction (2768°F) on the viscometer. In contrast, the Batch G slag showed much low viscosities of 200 poise at 2500°F and 67 poise at 2700°F. Figure 49 depicts the measured viscosity as function of temperature. T_{250} (temperature at 250 poise) is well below 2500°F for the Batch G slag. The low viscosity could be attributed to the presence of a surface-active constituent (such as dissolved sulfur or lime) during the slag formation. Also, the low viscosity could result in forcing the slag flowing up the sides of the combustor primary zone and lowering slag retention in the Batch G run. The higher surface tension of Batch G slag also indicated the difficulty reaching thermal/phase equilibrium between the flowing slag and the refractory-coated slag on the primary-zone wall surface. This resulted in a low slag retention.

A water-quenched slag obtained from a combustion run (Run No. 38) using Batch N was analyzed for its composition and ASTM fusion temperatures (Table 17). Run No. 38 was operated at 80 psig with a water quenched slag pit attached beneath the baseline combustor and

Figure 49. High-Temperature Viscosity Measurement for Batch 'G' Slag

Table 17. Properties of Water-Quenched Slag and Ash From Batch 'N' Fuel

	Water-Quenched Slag	Batch 'N' Ash
Composition, wt%		
SiO ₂	28.6	44.6
Al ₂ O ₃	49.8	22.6
TiO ₂	0.74	1.30
Fe ₂ O ₃	15.2	18.9
CaO	2.15	3.00
MgO	2.01	0.01
SrO	0.14	
Na ₂ O	0.731	1.50
K ₂ O	0.411	0.80
P ₂ O ₅	0.04	0.30
MnO ₂	0.03	
V ₂ O ₅	0.06	
PbO	0.03	
S (as SO ₃)	<0.02	
C	0.03	
Water-soluble Na ₂ O	0.003	
Water-soluble K ₂ O	0.001	
Al ₂ O ₃ /SiO ₂ Weight Ratio	1.74	0.51
Ash Fusion, Temperature, °F		
Reducing, Initial	2288	2144
Reducing, Softening	2311	2345
Reducing, Hemispherical	2385	2419
Reducing, Fluid	2575	2491
Oxidizing, Initial	2636	2490
Oxidizing, Softening	2651	2661
Oxidizing, Hemispherical	2695	2668
Oxidizing, Fluid	2700+	2676

with three torches heating the slag tap hole to prevent slag blockage. The measured fluid fusion temperature (under reducing atmosphere) was 2575°F which is within the desirable range in operation of a slagging combustor. This fluid temperature is somewhat elevated from the comparable point of 2491°F observed for the parent fuel ash. It is also clear from the composition analysis of the slag that a considerable amount of alumina contaminated from refractory had become incorporated somehow into the slag. The water-quenched slag had a Al₂O₃/SiO₂ ratio of 1.74 compared to the ratio of 0.51 from the Batch N fuel ash.

Two hot-end rig combustor samples were also determined for their composition and fusion temperature analyses (Table 18). The first was slag material located at the inlet of secondary combustion zone. The second sample was deposit material containing the exhaust-line ash/

Table 18. Composition and Fusion Temperatures of Slurry Ash and Hot-End Rig Combustor Samples

	Batch 'M' Slurry Ash	Hot-Eng Simulation Rig	
		Slag	Deposit Material
Composition, Weight %			
SiO ₂	49.6	49.4	46.3
Al ₂ O ₃	25.1	29.9	28.3
Fe ₂ O ₃	0.9	1.46	1.49
CaO	11.6	11.5	12.6
MgO	2.4	1.94	2.03
SrO	0.6	0.85	0.84
Na ₂ O	--	0.37	0.39
K ₂ O	1.9	2.36	2.50
P ₂ O ₅	1.9	1.68	1.64
MnO ₂	0.2	<0.02	<0.02
V ₂ O ₅	--	0.11	0.12
PbO	--	0.05	0.05
S (as SO ₃)	--	<0.03	<0.03
	3.5	0.45	3.70
Water-Soluble Na ₂ O	--	0.035	0.730
Water-Soluble K ₂ O	--	0.008	0.113
Ash Fusion Temperatures, °F			
Reducing, Initial	2205	2273	2226
Reducing, Softening	2265	2389	2372
Reducing, Hemispherical	2325	2535	2574
Reducing, Fluid	2632	2667	2686
Oxidizing, Initial	2560	2474	2410
Oxidizing, Softening	2650	2606	2594
Oxidizing, Hemispherical	2670	2697	2689
Oxidizing, Fluid	2687	2700+	2700+

particulate. Both samples were collected after the 4-hour run of HESR Test No. 4. Ash properties of Batch M slurry used in the test are also listed in Table 18 for comparison. The exhaust ash containing a higher SO₃ indicated that sulfate mineral tied with ash/particulate, especially with Na and K retained as water-soluble alkali sulfate salts. The fusion temperatures of combustion samples are about the same as those of its parent coal slurry ash.

Alkali in CWM Fuels

Alkali concentrations of coal-water slurries tested in the subscale combustor and the integrated bench scale facility are shown in Table 19. The combined alkali contents of sodium and

Table 19. Alkali Concentrations in Slurry Fuels

	Batch Number																	
	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	T	U
Sodium (ppmw)	142	170	38	149	673	240	220	291	378	251	248	246	190	143	177	190	176	182
Potassium (ppmw)	180	32	44	367	305	134	212	214	472	145	277	146	230	333	108	170	118	195
Total	322	202	82	516	978	374	432	505	850	396	525	392	420	476	345	360	294	377

potassium are in the range of 82-978 ppm. Heavy media separation cleans coal with 70% float and 30% refuse fractions. Table 20 shows the analysis of alkali concentration distribution starting from Kentucky 4A and Elkhorn coals as received. In parent coals, Kentucky 4A coal has about 642 ppm Na and 748 ppm K, and Elkhorn coal has 479 ppm Na and 582 ppm K. As slurry prepared with 54.5% coal cleaned via heavy media separation, the slurry ends up having 239 ppm Na and 156 ppm K. This is equivalent to an average of 62.2% alkali removed through a heavy media separation from raw coal to clean coal. With an addition of 18.7% alkali removal by an advanced cleaning (e.g., hot-water washing and/or dilute acid leaching), one would expect a total of 80.9% alkali removed from the original coal.

Table 20. Alkali Concentration Distribution

For a comparison, two Wyoming subbituminous coals - Kemmerer and Eagle Butte, cleaned by a combination of physical, chemical and hydrothermal processes (prepared by the University of North Dakota Energy and Mineral Research Center -UNDEMRC) were listed in Table 21. The alkali contents of the Kemmerer fuel is 45 ppm of sodium and 92 ppm of potassium with a total alkali of 137 ppm similar to the cleaned Eagle Butte coal. The processed Kemmerer or Eagle Butte coal could be presented as the low-alkali alternative fuel source (if needed) for the coal-fired gas turbine system.

Table 21. Comparison of Fuel Properties for Kemmerer and Eagle Butte Hydrothermally-Treated Subbituminous Coals

Coal Property	Kemmerer ^a	Eagle Butte ^b
Proximate Analysis, Dry %		
Ash	2.63	3.16
Volatile Matter	39.19	39.21
Total Sulfur, Dry %	0.36	0.31
Higher Heating Value		
Btu/lb (Dry)	12,479	12,553
Btu/lb (MAF)	12,616	12,963
Ultimate Analysis, MAF %		
Carbon	75.43	76.06
Hydrogen	4.40	4.64
Nitrogen	2.31	0.97
Sulfur	0.15	0.32
Oxygen	17.69	17.99
Total Alkali, Dry ppm		
Na ₂ O	60	60
K ₂ O	110	88
Ash Composition, %		
SiO ₂	59.1	51.0
Al ₂ O ₃	18.0	15.0
TiO ₂	0.62	2.0
Fe ₂ O ₃	8.10	19.8
CaO	4.25	2.45
MgO	1.99	0.32
SrO	0.35	0.09
Na ₂ O	0.23	0.19
K ₂ O	0.42	0.28
P ₂ O ₅	0.83	0.38
MnO ₂	0.03	0.05
PbO	0.06	0.03
V ₂ O ₅	0.4	0.05
SO ₃	7.05	0.62
T_{50%} B&W, °F	2850	2480
ASTM Ash Fusion Temperatures, °F		
Reducing, Initial	2146	2175
Reducing, Softening	2267	2320
Reducing, Hemispherical	2500	2375
Reducing, Fluid	2530	2482
Oxidizing, Initial		2340
Oxidizing, Softening		2490
Oxidizing, Hemispherical		2520
Oxidizing, Fluid		2530

^a Kemmerer minimum 15-micrometer HWD CSF prepared at UND Energy and Mineral Research Center.

^b From final project report for Contract No. DE-AC18-84FC10623.

The alkali content of test fuels introduced into the combustor causes corrosion and deposition problems associated with development of coal-fired gas turbines. The slagging combustor represents a technical advance the release of coal alkali minerals and retains the alkali with the slag. The overall balance for alkali control in a coal-fired gas turbine system is illustrated in Figure 50. Coal cleaning (e.g., hot water washing and dilute acid leaching) removes most soluble alkali, but will leave behind the majority of silicate-type alkalis. An operation of slagging combustor in conjunction with a particulate rejection impact separator (PRIS) could retain the coal mineral alkalis in the slag up to 85-95%. Portion of the unfixed alkali will stick with coal

Figure 48. Coal Alkali Concentration Distribution and Alkali Control in Slagging Combustion

particulate and be removed under the hot-gas secondary cleanup devices (e.g., ceramic candle, ceramic bag). The remaining vapor-phase alkali could further react and be captured by sorbents. Previous studies by other investigators have suggested that several aluminum oxides and silica dioxides (e.g., bauxite, kaolinite and emathlite) are promising sorbents for alkali vapor capture. Advanced coal cleaning as well as protective coatings and corrosion-resistant alloys applied for turbine-blades present other alternatives. The design goal was set for alkali vapor concentration less than 20 ppb with majority of alkali retained in nonleachable slag.

Alkali in Sorbents

Alkali in fresh sorbents has been analyzed for two dolomite samples and a hydrated lime. The results are shown in Table 22 indicating the sorbents contained only trace amounts of alkali and sulfur (inorganic). In particular, no sign of the anhydrite or sodium sulfate phases could be detected. X-ray powder diffraction analysis was further used to see if any various sulfates could be identified. As expected, the results showed sorbents containing predominantly (>90%) dolomite $[\text{CaMg}(\text{CO}_3)_2]$. There is no evidence on the X-ray pattern for anhydrite (CaSO_4) or any of the sodium sulfates found in the fresh sorbents.

Table 22. Properties of Dolomite and Hydrated Lime Sorbents

	Dolomite D-303	Dolomite D100	Hydrated Lime
Composition, %			
Na ₂ O	<0.001	<0.001	0.010
K ₂ O	<0.001	0.002	0.028
X-Ray Diffraction			
Dolomite	Predominant		
Calcite	Trace		
Anhydrite	None Detected		
Sodium Sulfate Phases	None Detected		

5.2.2 Coal Cleaning Technology

Coal Source Selection

Potential coal sources are being identified for major market areas of industrial gas-turbine cogeneration system. The quality and cost of source coals suitable for the system were evaluated. Table 23 shows a list of target coal which samples have been obtained for coal properties and ash/slag characterization.

Bituminous coal from Utah appears to have the best potential for consumption in the California market. Coal from Utah's Soldier Creek Mine has been selected as the example source coal. The Soldier Creek Mine is the Prince/Helper area of Utah. As shown in Table 24, the coal is a high-volatile low-sulfur bituminous coal that can be washed down to about 5% ash with an ASTM reducing-atmosphere fluid temperature of about 2560°F.

Modification of Slag Properties

Magnetite and lime as additives have been tested for the purpose of adjusting the ash fusion temperatures of coal fuels. Figure 51 plots the ash fluid fusion temperatures (under reducing atmosphere) as a function of weight percent of additive. The plot could be served as a guideline to determine the amount of additive needed for the ash fusion temperature adjustment during the slurry fuel preparation. In general, with less than 0.05 wt% of lime addition, the ash fluid temperature could be dropped significantly within the ranges specified in the fuel specification of slagging combustor (2400-2700°F). However, on a same weight basis, magnetite is less effective than lime for lowering fusion temperatures of the fuels. In contrast, the addition of alumina could raise the ash fusion temperatures to the desirable range.

Table 23. Coal Source

Market Area	Coal Seam or Location	Mine Source
Pennsylvania/New Jersey/Ohio	Pittsburgh Seam	Bailey Powhatan
	Central West Virginia	Kelley Creek Grauley-Eagle
	Kentucky Splint	Arch
	Kentucky 4 and 5	Prince Elkhorn
Illinois/Indiana/Missouri	Illinois No. 6	Delta
	Illinois No. 5	Inland
Texas	Rogers Country, Oklahoma	Croweburg
California	Price Utah Area	Soldier Creek Castle Gate
	Wyoming	Kemmerer Eagle Butte

Figure 51. Fluid Fusion Temperature as a Function of Weight Percentage of Lime or Magnetite Addition

Table 24. Properties of Utah's Soldier Creek Coal

	Soldier Creek Coal		
	As-Received	1.4 Sp Gr Float	Froth Flotation
Yield, dry wt%	100.0	64.3	77.8
Proximate Analysis, dry wt%			
Ash	10.50	3.57	5.36
Volatile Matter	36.02	38.75	37.78
Fixed Carbon	53.48	57.67	56.85
Forms of Sulfur, dry wt%			
Total Sulfur	0.522	0.521	0.492
Pyrite Sulfur	0.049	0.016	0.041
Sulfate Sulfur	0.007	0.008	0.040
Heating Value, Btu/lb			
Dry	12948	13634	13642
Moisture and Ash-Free	14487	14346	14415
Hardgrove Grindability Index	49		
Ultimate Analysis, dry wt%			
Carbon		78.55	77.22
Hydrogen		5.20	4.98
Nitrogen		1.36	1.41
Sulfur		0.52	0.49
Ash		3.57	5.36
Oxygen		10.80	10.54
Ash Composition, %			
SiO ₂		56.4	53.8
Al ₂ O ₃		17.9	21.9
TiO ₂		1.07	1.60
Fe ₂ O ₃		3.37	3.94
CaO		5.46	5.56
MgO		1.03	1.22
SrO		0.26	0.20
Na ₂ O		1.10	0.703
K ₂ O		0.375	0.904
P ₂ O ₅		0.85	0.69
MnO ₂		0.011	0.018
V ₂ O ₅		0.020	0.028
PbO		0.015	0.024
SO ₃		6.29	5.28
Water-Soluble Na ₂ O		0.014	0.052
Water-Soluble K ₂ O		0.020	0.027
Ash Fusion Temperature, °F			
Reducing/Oxidizing			
Initial		2307/2394	2303/2568
Softening		2349/2418	2333/2424
Hemispherical		2365/2448	2412/2542
Fluid		2532/2537	2561/2648

A study of the effect of slag modifier (i.e., alumina) on the ash fusion properties was conducted on a Midwestern coal. A lot of Illinois No. 6 from the Delta Mine was cleaned by froth flotation. The ASTM reducing atmosphere fluid temperature of the ash in the clean coal was found below 2400°F, which is typical for most Midwestern coals. Slurry fuels were prepared from the clean Illinois No. 6 coal with or without a hydrated alumina addition equal to 50% of the original coal ash weight. The properties of the resulting ash samples are given in Table 25. Slag viscosity and surface tension measurements (by UNDEMRC) were also attempted on the sample. Figure 52 plots the viscosity of non-additive ash sample under air and reducing atmosphere. The sample determined under air showed much higher viscosity than those under reducing atmosphere, but the viscosities were about the same at temperatures above 2650°F under both conditions. The following measurements were obtained in a CO-rich reducing atmosphere for the ash from the fuel without added alumina:

Ash Fluid Temperature	: 2362°F (Reducing)
Viscosity at 2500°F	: 1867 poises
T ₂₅₀ (measured)	: > 2730°F
Surface Tension @ 2102°F	: 352.3 dynes/cm

The viscosity measurements are higher than what would normally be predicted for Illinois coal by the T₂₅₀ methods, as shown also in Table 25. During slag viscosity measurements, sample with added alumina (added as 50% of coal ash weight) was heated to a maximum working temperature, but it could not be fused despite the fact that the reported ASTM reducing atmosphere fluid temperature is 2635°F. Another attempt was made to prepare a modified slurry with a hydrated alumina addition equal to 25% of the original ash weight to adjust the slag viscosity. The results of ash viscosity measurement in a CO-rich reducing atmosphere and in air are plotted in Figure 53. The measured viscosity at 2600°F was 620 poises for the modified ash compared to 480 poises for the original coal ash (as depicted in Figure 52). The values of T₂₅₀ for both of the modified and non-modified ashes were well above the upper-scale of measurable temperature of viscometer.

Being able to modify the ash fusion properties of prospective source coals in a predictable manner will have a significant impact upon the availability of usable feedstocks for manufacture of slagging combustor fuels.

5.2.3 Pilot-Scale Cleaning Tests

Fuel Manufacturing/Column Flotation

Column flotation in slurry fuel manufacturing tests were performed to reduce the fuel cost by increasing the coal recovery and reducing the ash content. The previous results have shown that high BTU recoveries are possible at the same ash levels achieved in the heavy media separation. Clean coals containing between 3 and 4% ash are being produced from minus 45 µm Kentucky 4A coal at approximately 90% yield. This is about the same ash content as the clean coal produced from Kentucky 4A coal by heavy-media washing, but the coal yield is improved by at least 50% when cleaning by column flotation. Additional tests were conducted on investigation of the effects of aeration rate, volumetric feed rate/retention time, frother additive, froth depth, and wash water ratio on the performance of the column flotation rig (Figure 54).

Table 25. Properties of Ash From Illinois No. 6 Clean Coal Fuel With and Without Hydrated Alumina Addition

	Illinois No. 6 Clean Coal Ash	
	Without Alumina	With Alumina
Composition, Wt%		
SiO ₂	57.3	43.7
Al ₂ O ₃	18.0	36.4
TiO ₂	1.14	0.84
Fe ₂ O ₃	19.9	15.0
CaO	2.55	2.21
MgO	0.85	1.05
SiO	0.01	0.01
Na ₂ O	0.29	0.25
K ₂ O	2.55	1.85
P ₂ O ₅	0.18	0.25
MnO	0.04	0.04
V ₂ O ₅	0.09	0.08
PbO	<0.06	0.06
SO ₃	2.15	0.10
Base/Acid Ratio	0.34	0.25
SiO₂/Al₂O₃ Ratio	3.18	1.20
ASTM Ash Fusion Temperature, °F		
Reducing, Initial	1994	2486
Reducing, Softening	2073	2559
Reducing, Hemispherical	2132	2576
Reducing, Fluid	2362	2635
Oxidizing, Initial	2318	2700+
Oxidizing, Softening	2480	2700+
Oxidizing, Hemispherical	2495	2700+
Oxidizing, Fluid	2547	2700+
Reducing Atmosphere Fluid Temperature, AMAX R&D Calculation, °F	2337	2650
T₂₅₀, °F		
B&W Graphical	2480	2620
Silica ratio Calculation	2543	2530
Measured (UNDEMRC)	2730+	>>2730*
Slag Viscosity at 2500°F, Poise		
B&W Graphical	ca 250	>250
Silica Ratio Calculation	322	300
Measured (UNDEMRC) at 2500°F	1867	~1500
at 2600°F	480	620
Slag Surface Tension, dynes/cm	352.3	Solid
*Ash would not fuse at 2730°F in the UNDEMRC system even when surrounded by a reducing atmosphere.

Figure 52. High Temperature Viscosity Measurements for Illinois No. 6 Coal (Delta Mine) Ash Under Air and Reducing Atmosphere

An examination of the data indicated that low aeration rates and low frother additives enhance ash rejection. It was also found that the coal content of the feed slurry could be higher (>2 liters/min) than first thought without adversely affecting performance. This will have a favorable impact upon the unit capacity of the system. The volume of air hold-up in the column was measured at a number of operating conditions. It was found that the volume of slurry displaced by the air during operation is an important parameter on performance when calculating retention times and flotation rate constants. The results of various wash water ratio further suggested that large volumes of wash water decreased slurry residence time, which was beneficial for rejecting ash.

However, additional tests on Kentucky 4A and Illinois No. 6 coals results in finding the amount of wash water sprayed on the top of the froth column is the most important operating variable to impact column performance. Variations in the frother dosage, aeration rate, solids concentration, froth depth, and particle size were also found to affect the flotation rates, hence the capacity of the system. Optimum wash water ratios (5 to 6 liters of spray water per kg clean coal), aeration

Figure 53. High Temperature Viscosity Measurements for Illinois No. 6 Coal Ash With Alumina Additives

rates (80 to 160 liters of air per kg feed coal), and froth depths (100 to 120 cm) were identified which would minimize the ash content of the recovered coal. Low frother additions and solids concentrations were found to be preferred conditions for rejecting ash, but optimum values for these variables (if any) were outside the range of the operating conditions investigated during the testing. The following points on the optimized grade-recovery curve are being projected at this time for column flotation systems cleaning minus 45-micrometer Kentucky and Illinois coals:

	Feed Coal Ash, %	Clean Coal Ash, %	Yield, %
Kentucky 4A	7.0	2.5	80.0
Kentucky 4A	7.0	3.4	90.0
Illinois No. 6	12.0	5.4	80.0
Illinois No. 6	12.0	7.4	90.0

Figure 54. Column Flotation Apparatus

Combustion Fuel Improvement

Preparations of 14 improved fuels for combustion were scheduled. These fuels were formulated with important fuel characteristics to improve combustion performance and to finalize the target fuel specification. The schedule consists of a base case fuel, four series of formulations which are variations of loading/ash content, particle size, rank/reactivity, and ash fusion properties. An optimized fuel for the combustion test would be prepared following the best procedure and formulation from the test results. A target fuel specification will be developed based on the identified fuel properties for the full-scale engine testing. This fuel specification shall be submitted to COTR for review and approval.

The proposed base case fuels were prepared from the blend of Kentucky 4A/Elkhorn coal with or without the addition of stabilizer. Four drums each of the two performance testing baseline fuels were manufactured. Batches S-1 to S-9 were prepared and analyzed. These fuels were prepared to show the effects of the presence of reagents, loading, ash content, and particle size distribution. The following is a summary of the properties of the fuels prepared so far.

<u>Fuel No.</u>	<u>Loading Weight, %</u>	<u>Dry Ash, %</u>	<u>Top Size, μm</u>	<u>Mean, μm</u>	<u>Stabilizer</u>
S-1 (Baseline Fuel)	54.2	3.77	38	10.8	Yes
S-2	54.2	3.77	38	10.8	No
S-3	58.2	3.98	50	12.7	Yes
S-4	50.0	4.03	45	11.4	Yes
S-5 (No Dispersant)	43.4	3.96	60	15.4	No
S-6	53.6	8.84	38	8.8	Yes
S-7	53.6	12.81	38	9.3	Yes
S-8	53.8	3.85	25	7.3	Yes
S-9	53.8	3.93	50	15.4	Yes

Batch S-2 is the same of Batch S-1 (baseline fuel) except that the Flocon stabilizer was omitted from the formulation. Batches S-3 and Batch S-5 were prepared by blending coarsely and finely ground slurries to achieve the "bimodal" effect for obtaining a high solids loading. Batch S-3 was formulated at 58.2% coal, that seems to be the maximum loading which can be achieved for this blend of coal which still meet the fuel viscosity specification requirement. Batch S-4 was prepared with a loading of about 50% coal, while Batch S-5 was formulated without dispersant and stabilizer which containing only 43.4% of coal loading. The other two batches, S-6 and S-7, were prepared with higher ash contents. Batch S-6 contained 4.80% ash (or 8.84% ash on dry coal basis) and Batch S-7 contained 6.96% ash (or 12.81% on dry coal basis). These two coal ash contents are about double or triple amounts of baseline fuel. Batch S-8 had a particle top size of 25 μm and mean size of 7.3 μm and Batch S-9 has 50 μm and 15.4 μm , respectively.

Fuel Cost Updated

The projections of fuel production costs first were made in 1987 and updated recently. The general picture is that capital costs have gone up approximately 10% since early 1987. The costs of coal, transportation, and many operating supplies have been steady, while labor and other costs have risen moderately. On the other hand, process improvements and process simplicity have resulted in saving for slurry preparation so that the overall fuel cost to users is unchanged to down 35 cents per million Btu since 1987, depending upon the plant location, production rate, and fuel quality scenario assumed for the comparison.

Table 26 updates the fuel cost based on various fuel supply and requirement scenarios. As shown in the table, the fuel costs are sensitive to the fuel plant location and capacity, and to the ash content of coal. Decreasing the size of plant to produce fuel for fewer turbine users would increase the cost considerably. The fuel costs are also sensitive to the location of coal fuel plant and the freight cost of coal fuel transportation. Low transportation charges would result if the fuel

Table 26. Coal Fuel Delivery Cost (1989 - \$/MMBtu)

Fuel Type	Mine Site			Central Site			On-Site	
	100 MW	25 MW	15 MW	100 MW	35 MW	15 MW	4 x 3.8 MW	3.8 MW
Slurry - 50% Solids								
7% ash, 100 μ m	2.89	3.31	4.03	3.18	3.84	4.44	3.60	6.08
3% ash, 100 μ m	3.16	3.64	4.46	3.51	4.04	4.93	4.11	7.33
0.6% ash, 100 μ m	5.13	6.10	—	5.55	6.55	—	—	—
7% ash, 44 μ m	3.24	3.63	4.31	3.53	3.95	4.72	3.88	6.75
3% ash, 44 μ m	3.51	3.51	4.73	3.86	4.33	5.20	4.38	8.00
0.6% ash, 44 μ m	5.38	5.38	—	5.79	6.64	—	—	—

was delivered by rail direct to a large multiple turbine installation, while high charges would result if the fuel was delivered by truck to a single turbine installation. Other factor impacts on the fuel cost is the degree of coal cleaning. The coal cleaning between minimally cleaned (7% ash) and deep cleaned (3% ash) fuels does not have a significant effect on the cost. However, there is a remarkable increase of fuel cost for the maximally cleaned fuel (0.6% ash). Furthermore, moderate saving will result from specifying 100-micron rather than 44-micron grinding size. A case selected for a slurry fuel with central site preparation/truck transportation can be commercially produced at \$3.18 per million Btu. The cost of a fuel with mine site preparation/rail delivery is projected for as low as \$2.89 per million Btu.

Integrated Full-Scale Fuel System

An integrated fuel supply system for the full-scale 100-hour engine testing is being considered. The benefit of such arrangement is that a slurry fuel can be prepared on-site and directly pumped into the combustor after coal grinding without major off-site fuel preparation and storage. A reduction or elimination of the need for additives could be achieved. For the full-scale tests at CWM feed rate of 6000 lb/hr, the grinding capacity rate of coal has to be around 1.6 tons/hr or equivalent to a slurry flow rate of 600 gallons/hr. The flowsheet of the integrated system is depicted schematically in Figure 55.

Figure 55. Integrated Fuel System in Coal-Fueled Gas Turbine

Figure 56. Plot Plan of Integrated Coal Fuel Processing by the Turbine Site

This configuration, which used a conventional mill and no beneficiation, requires suitable grinding equipment while benefitting from reduced coal fuel handling and storage costs. Figure 56 shows a plot layout where coal would be received on-site, unloaded, and ground into slurry fuel prior to combustor. A boiler-grade coal (70% of 200 mesh) or washed coal (1/2 mm top size) will be unloaded from dump trucks and transported by front-end loader to mill feed-hopper.

To make the slurry, coal will be ground with a stirred ball mill consisting of a chamber with small grinding beads (1-10 mm). The Drais Perl Mill, as an example of commercial available unit, is a higher speed version of the stirred ball mill which could continuously grind coal without premixing. It differs from the conventional stirred ball mill in that there are pins projecting from the stationary chamber which interact with the pins in the stirring shaft. The feed material enters the bottom of the chamber in the form of coal and water mixture. The feed particles in the mixture are ground by the action of the balls, the stationary pins and the rotating stirrer. The ground material works its way up to the top of the chamber and exit as a coal-water slurry. Prior to the grinding, dispersant reagent (if necessary) can be mixed with water to adjust the output slurry with desirable rheological properties.

Other types of grinding mills are also being evaluated so that suitable capacity of fuel supply equipment could be integrated in the full-scale combustor system. Budget price quotations for grinding equipments have been requested from Draiswerke, Inc., Netzsch, and Union Process, Inc., manufactures of stirred ball mill grinding machine. The impact of integrated fuel system are under studied, especially on:

- Boiler-grade or washed coal availability,
- Space requirement for coal stockpile,
- Environmental regulation permits, and
- Capital investment return of grinding equipments.

The availability of boiler-grade or washed coal with the particle size of 2 mm (or 10 mesh x 0) as the feedstock is a major concern; otherwise, a crusher prior to the stirred ball mill will be required to grind the run-of-mine washed coal (2-inch x 0) to the smaller size.

In order to justify the purchase of full-scale fuel preparation equipment, the following table briefs a comparison of the capital cost and fuel-purchase price on a basis of 100-hr and 500-hr engine tests.

Grinding Mill

Specifications:

Feeding rate	8,800 lb/hr 880 gallons/hr
Grinding chamber capacity	40.2 gallons
Overall dimensions	
Length	8.7 ft.
Width	8.3 ft.
Height	12.0 ft.
Weight	14,330 lb
Power required	
Agitator	100-132 kW
Screw feeder	24 kW

Costs with Integrated Grinding Mill:

	Case I: 100-hr Testing	Case II: 500-hr Testing
Grinding Mill	\$ 348,000	\$ 348,000
Support Equipment & Installation	\$ 80,000	\$ 100,000
Coal Cost (@ \$50/ton)	\$ 7,500	\$ 37,500
Coal Transportation Cost	\$ 50,000	\$ 245,000
Labor (manpower @ \$50/hr)	\$ 5,000	\$ 25,000
Utilities	\$ 1,500	\$ 7,500
	<hr/>	<hr/>
	Σ \$ 492,000	Σ \$ 763,000
Others (@ 10%)	\$ 49,200	\$ 76,300
	<hr/>	<hr/>
Total	\$ 541,200	\$ 839,300

For a 100-hr full-scale engine testing, an integrated on-site fuel preparation system will cost about \$541,000; this number jumps up to \$839,000 for a 500-hr testing. The above cost analyses for the integrated grinding-mill cases are based on a boiler-grade coal (70% of 200 mesh) or washed coal (1/2 mm top size) at a price of \$50/ton available on the utility market. If not, then coal would be purchased at \$25 per ton (7% moisture, 2 x 0 inch) on an open market, but a crusher for size reduction will be required prior to the final grinding. Under these considerations, the costs of feeds (at \$50/ton vs at \$25/ton + crushing cost) going into the finish grinding are assumed to be about the same. The analysis also includes an extra of 1/2 man-power labor cost required for the grinding-mill on-site operation compared to the case of purchasing slurry fuel operation.

In the case of purchasing fuel from slurry manufacturing company, the 100-hr testing (60,000 gallons) would cost about \$1,123,000 and for 500-hr it goes up to \$5,615,000, as estimated below:

Costs with Purchasing Fuel:

	Case I: 100-hr Testing	Case II: 500-hr Testing
Fuel cost	\$ 900,000	\$ 4,500,000
Transportation cost	\$ 120,000	\$ 600,000
Tanker trailer holding cost	<u>\$ 1,000</u>	<u>\$ 5,000</u>
	Σ \$ 1,021,000	Σ \$ 5,105,000
Others (@ 10%)	<u>\$ 102,100</u>	<u>\$ 510,500</u>
Total	\$ 1,123,100	\$ 5,615,500

6. PHASE II - TASK 6 - HOT END SIMULATION

6.1 SPECIFIC ITEMS OF PROGRESS

- Completed fabrication of injector version 4A. Three guiding spokes were added near the injector tip to center the fuel tube which improved atomization. High pressure atomization tests confirmed the expected decrease in droplet size. Ran injector in HESR combustor. After three hours on CWM, the injector plugged and the run was aborted.
- Fabricated injector version 5 which does not incorporate water cooling as in version 4A. Flow and atomization tests performed with the injector yielded promising results with a mean droplet size of 12 microns. The injector has performed successfully in combustor tests and has now logged over 50 hours on CWM.
- Evaluation tests were run with a single Schumacher dia-Schumalith candle installed in the filter vessel. Purge systems and pulse duration have been modified to improve filter cleaning performance.
- The material sample section has been installed and one test has been run with it in place. With low sample section inlet temperatures being measured, investigative work has been done to add supplemental heat to this area to bring it up to temperature.

6.2 DISCUSSION

Efforts on the Hot End Simulation Rig, shown in Figure 57, were dominated by development work. Table 27 documents Hot End Simulation Rig testing for the past year. Injector improvement was of greatest concern. Fabrication of fuel injector version 4A, shown in Figure 58(a), was completed. In order to improve atomization, three guiding spokes were added near the injector tip to center the fuel tube inside the assembly. High pressure atomization tests confirmed the expected decrease in droplet size. The injector was instrumented and run in the Hot End combustor. After 3 hours on CWM there was a sudden increase in injector temperature which was the most likely cause of the subsequent plugging of the injector. A water purge was added to the fuel feed manifold to periodically clean the fuel tube. A second run with injector version 4A was attempted. Soon after switching over to coal, the injector plugged; the water purge was ineffective and the run was aborted. Injector version 5 was designed to resolve this problem.

A model of injector version 5 was manufactured. This injector uses an air assist annulus to aid in atomization and to shield the fuel tube, down to the tip, from the heated primary air and is shown in Figure 58(b). Successful atmospheric flow tests were performed using the model injector. A new CWM fuel, AMAX Batch 'R', which does not contain a stabilizer, was used for these tests. With Batch 'R' the CWM feed system strainers were not blocked with gummy material that is typically present when fuel containing stabilizer is used. The two tests were run for a total of 8 hours on CWM without problems. Because of the exceptional results using version 5 along with Batch 'R', AMAX prepared 3 barrels of the slurry to be used for the HESR. Development of injector version 5 continued with atomization tests using the model. At settings close to design conditions, a 25 micron mean droplet size was achieved. These results confirmed the viability of version 5 and an injector was fabricated.

Figure 57. Schematic of Hot End Simulation Rig

Atomization tests were performed with the HESR injector version 5. As with the model, test results were superior with mean drop sizes of 12 microns and 90% of the drops less than 50 microns. A two hour atmospheric test yielded exceptional results using Batch 'R'. No injector problems were encountered. Prior to the next HESR test with injector version 5, a water quench system was added to the combustor exhaust to facilitate cooling at the exit.

HESR - 8 used injector version 5 and AMAX Batch 'R' fuel. The combustor operated smoothly at 94 psig with the CWM flow rate set at 20 lb/hr. The test was voluntarily terminated after running a total of 5 hours on CWM, burning 98.6 lbs. Having successfully completed HESR - 8, emissions data would be collected in HESR - 9 using the same injector and batch fuel. Again, the combustor ran smoothly at 94 psig and an inlet air temperature of 580°F. The equivalence ratio in the primary zone was relatively constant at 1.34. The combustor outlet temperature peaked at 1920°F. As shown in Table 28, the emissions data are exceptional with low NO_x , CO, and UHC. Plugging of the gaseous emissions sampling probe reduced the number of CWM emissions points, however, the data gathered surpassed all requirements. Post test inspection

Table 27. Summary of Hot End Simulation Rig Testing

Test No.	6	7	8	9	11 ¹	12	13	14	15	16
Objective	Evaluation of Injector Version 4A	Evaluation of Injector Version 4A	Evaluation of Injector Version 5	Evaluation of Injector Version 5	Injector Endurance Test	Candle Test	Test Higher Candle Purge Pressures	Retest of No. 13	Evaluation of Modified Purge System	Evaluation of Sample Section Heating
CWM Batch	'M'	'M'	'R'	'R'	'R'	'R'	'R'	'R'	'R'	'R'
Hours on CWM	3:00	0:15	5:00	6:00	11:30	4:00	3:33	2:09	4:00	19:05
P _h (psig)	79	82	85	90	85	83	83	82	83	83
T _{exhaust} (°F)	1700 ²	N/A	1733	1920	1100	600 ³	800	860	900	1300
↓ primary	1.18	N/A	1.18	1.20	1.21	1.16	1.22	1.23	1.35	1.25
¹ Test No. 10 terminated due to data acquisition system difficulties. ² Exhaust temperatures measured downstream of secondary zone. ³ Filter vessel and material sample section in line. Exhaust temperatures measured downstream of sample section.

(a) Version 4A

(B) Version 5

Figure 58. HESR Fuel Injector Design Modifications

Table 28. HESR - 9 Emissions Data

Fuel	Batch 'R'
T _{in} (°F)	580
P _{in} (psig)	94
Φ _{primary}	1.34
T _{outlet} (°F)	1705
Emissions @ 15% O ₂ ppmv, (lbs/mmBtu)	
NO _x	30.98 (0.1390)
CO	1.83 (0.0047)
UHC	5.96 (0.0070)
SO ₂	Not measured
Slag Rejection	Not measured
Carbon Conversion	Not available

of the combustor revealed slag freezing around the slag tap hole inhibiting molten slag to flow into the slag pit. Installation of torches directed at the slag tap hole were expected to resolve this problem. Examination of the secondary zone showed no slag escape or plugging.

Due to a change in personnel, a 12 hour injector endurance run was performed without the filter vessel in line to reinforce the viability of version 5 and gain operational experience. During CWM operation, the primary zone equivalence ratio was fairly constant at 1.32 and exhaust temperatures were 1100°F, typically. At the 11.5 hour mark the injector plugged momentarily, stopping the CWM flow, but was quickly cleared of fuel and the normal diesel shutdown procedure was followed. Total time on CWM was 11.5 hours burning 260.0 pounds. Due to the successful results achieved using injector version 5 with CWM Batch 'R', Amax was contacted to supply slurry fuel with characteristics similar to Batch 'R' for future HESR tests. Batch 'R' characteristics are shown in Table 29. Upon teardown of the rig, inspection revealed some slag accumulation on and around the impactor. Also, a measurable amount of bottom ash was observed in the slag pit. This material amounted to about 2.5 lbs and was quite light having a bulk density of only 11.5 lbs/cu ft. Analytical data indicate that the material was 47.2% carbon and 52.8% ash. The 2.5 lbs of material amounted to about one percent of the entire CWM fed to the system, or roughly 2 percent of the fuel on a dry basis. Because of the extremely low bulk density of the material, it is possible that removal of the material during long duration runs will be required.

Table 29. CWM Batch 'R' Characteristics

Coal Seam	Kentucky 4A	
Coal Loading (wt%)	54.34	
Ash Content (wt%)	2.07	
Ash in Slurry (%)	2.2	
Particle Top Size (μm)	45	
Particle Mean Size (μm)	10.4	
Slurry LHV (Btu/lb)	7,855	
Slurry Viscosity (cp)		
@ 100 sec ⁻¹	150	
@ 1000 sec ⁻¹	190	
Proximate Analysis of Coal (wt%)		
Volatiles	34.82	
Fixed Carbon	61.28	
Ash	3.9	
Ultimate Analysis of Coal (%)		
C	84.09	
H	5.56	
N	1.78	
S	0.92	
O	7.66	
Ash Fusion Temperature (°F)		
	<u>Oxidizing</u>	<u>Reducing</u>
Initial Deformation	2672	2387
Softening	2694	2419
Hemispherical	2700	2467
Fluid	2700	2651

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

During HESR-12, the rig was operated for 4 hours with a single Schumacher dia-Schumalith candle filter in-line. After the run, the candle was removed for inspection. The dust loading in the Hot End Rig is fairly low as there is no sorbent injection system. As a result, the load on the candle filter is significantly reduced and purging is not often required. In fact, the pressure drop measured across the tube sheet did not exceed 2 psid for the entire test. Purging is typically initiated when the differential pressure has reached about 3 psid. Nonetheless, cleaning of the

candle was tested with purge pressures of up to 200 psig (combustor pressure was about 90 psig throughout the test). At these pressures, there was no apparent change in the differential pressure across the tubesheet. When the candle was removed, a thin layer of dust was observed on most of the candle. This was removed readily from the candle and was analyzed. Moreover, dust was observed at the bottom of the filter vessel. Apparently, some cleaning of the candle did take place. The incomplete cleaning of the filter, however, was most likely the result of purge pressures that were too low.

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

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

An area of concern, especially for long term runs, involves the impactor spool and the slag pit. Temperatures measured in these regions have been consistently too cool to allow the slag to flow, and as a result, slag has filled the impactor area and, on occasion, part of the primary zone. The installation of torches directed at the impactor area did not resolve the matter. In order to combat the problem, a new impactor spool piece which incorporates several insulating and refractory materials was investigated. Cones of Kaocrete HPM 90, Kaolite 280C, and Kaolite 2300 will make up the impactor area. The concept was to keep the slag tap hole hot enough to maintain slag in the molten form to flow down into the slag pit. To further enhance the heat supplied, investigative work is underway to cast heating elements into the refractory of either the impactor spool or the slag pit itself.

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

The HESR was operated over 24 hours on diesel and coal water slurry in HESR-16. A total of 422 lbs. of CWM was burned over a period of 19 hours. Sample section temperatures increased throughout the run as the gas inlet temperature to the sample section reached 1500°F. Inlet filter vessel temperatures reached 1900°F, but downstream sections were much cooler. These temperatures over time are shown in Figure 59. Silicon carbide heating elements are being examined for use in heating the gas stream at the inlet of the sample section and keeping the temperature drops to a minimum. The two 1100°F and two 1200°F coupons in the material sample section required the metering in of cooling air to obtain their setpoints. The 1300°F coupons were close to their setpoint although cooling air was not necessary. Temperature controllers and proportional solenoid valves are being obtained to accurately control the temperature of the material coupons.

Figure 59. HESR 16 Temperature of Filter Vessel Inlet, Candle, and Sample Section

Candle performance was of great interest during this run. The candle filter saw gradually increasing temperatures throughout the run. The peak temperature at the filter vessel inlet was recorded at 1370°F, although temperatures in the downstream, or clean, side of the candle reached a peak of 1776°F. Purging cycles were effective in cleaning the filter initially, yet ineffective towards the end of the run. The differential pressure across the candle filter reached about 5 psid; at this point the candle became very difficult to clean. Subsequently, a shutdown procedure was initiated. It is not clear if the candle is blinding or if reentrainment is a contributing factor. The nature of the dust collected and the fact that the candle appeared fairly clean indicates that gradual blinding is more likely the cause. During the run, the backside of the candle was observed through a window and appeared clean. However, the side near the inlet piping had an accumulation of ash which did not come off with purging, even at pulse pressures of up to 290 psig. To prevent this from occurring again, a shroud of RA330 will be welded to a spacer near the tubesheet to protect the candle from direct impingement of dust.

Upon post-test inspection of the rig, very little accumulation of slag was observed in the secondary combustor area. Particulate was collected from the bottom of the filter vessel. This particulate was comprised of a fairly cohesive dust which was purged from the candle during the earlier stages of the run. On top of this dust was observed additional particulate which had

retained the shape of the candle, indicative of the very cohesive dust. These pieces were generally about an inch or so in length and very hard and glass-like. Analyses of both particulates is underway.

Another area that needs attention is the exhaust section. The back pressure valve displayed an inordinate amount of corrosion presumably due to acid attack. During the run, it became necessary to control the pressure of the rig using two ball valves in conjunction with the back pressure valve. Unfortunately, the ball valves experienced the same corrosion. Since no sorbent is utilized, nearly all of the sulfur in the coal is converted to gaseous sulfur dioxide. The back pressure and ball valves were exposed to the gas below the dew point. This will be resolved by employing an alkaline filter of some kind, and by implementing acid resistant materials at the appropriate locations in the system.

In conclusion, there exists a proven injector and batch fuel to be used for future tests. However, rig reliability is a major concern. Slag accumulation in the impactor area will be reduced by the incorporation of heating elements which are under examination. The material sample section inlet temperature will be brought up to design point, representative of DCFT gas, through the addition of silicon carbide heaters. And, with the implementation of acid resistant materials for valves and the like, the HESR will be prepared for its 1000 hour run.

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APPENDIX A

SUMMARY OF CWM TEST FUEL PROPERTIES

Coal	C	D	E	F	G	H
Source	80% Kentucky 5 20% Elkhorn	80% Kentucky 5 20% Elkhorn	Spirit	Powhatan	Powhatan with 5.3% Lime	75% Clean Elkhorn 25% Reed Elkhorn
Coal content (wt%)	54.10	55.50	55.50	50.50	49.50	54.09
Ash Content (wt%)	2.10	1.39	1.70	3.40	7.50	1.25
Particle Content						
% Passing 100 micron	100.00		99.50	100.00	100.00	
% Passing 75 micron		99.10	99.70	100.00	100.00	
% Passing 45 micron			90.00	99.50	99.50	99.50
% Passing 37 micron			71.50	99.70	99.70	99.50
% Passing 25 micron			93.70	99.50	99.50	99.50
% Passing 15 micron			55.40	74.00	74.00	90.50
% Passing 5 micron			34.00	38.00	78.00	55.50
% Passing 4 micron						44.70
% Passing 3 micron						33.50
% Passing 2 micron						29.50
% 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	7515	7758	5190	7245
Proximate Analysis (wt%)						
Ash	3.98	2.30	3.03	5.92	13.82	2.30
Volatiles	36.10	34.80	37.40	37.51	36.43	31.70
Fixed Carbon	60.02	62.97	59.57	56.57	47.74	66.00
Ultimate Analysis						
Carbon	77.10	84.18	81.20	81.44	83.38	85.82
Oxygen	14.38	8.38	8.45	8.68	6.18	7.35
Hydrogen	5.80	5.38	4.91	5.25	5.67	5.09
Nitrogen	1.82	1.84	1.51	1.50	1.53	1.15
Sulfur	0.90	0.85	0.80	3.13	3.26	0.59
Ash Composition						
SiO ₂	53.00	40.30	45.50	42.80	13.50	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	20.50	7.10	10.90
CaO	1.36	5.02	5.15	1.91	18.20	4.00
MgO	0.51	1.10	1.39	0.42	11.40	0.05
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	0.48	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	2570/2480	2305/2233	2395/2140	3452/2485	2512/2000	2515/2250
Softening	+2700/2605	2393/2286	2530/2275	2502/2480	2544/2183	2665/2275
Hemispherical	+2700/2650	2521/2356	2450/2305	2518/2457	2559/2351	+2700/2350
Fluid	+2700/2700	2555/2494	2518/2495	2518/2495	2563/2440	+2700/2510

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	53.83	54.88
Ash Content (wt%)	2.15	2.11	2.15	2.15	1.78	2.21
Particle Content						
% Passing 100 micron	99.90		100.00			
% Passing 74 micron	99.80		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	83.40	89.30	80.80	88.80	99.90	95.90
% Passing 15 micron	39.20	73.30	50.80	88.40	91.80	75.90
% Passing 5 micron	22.80	37.30	34.30	37.10	85.20	42.10
% Passing 4 micron		30.00			54.40	31.20
% Passing 3 micron		21.00			40.80	23.30
% 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	8.80	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	596.00			370.00	435.00
Slurry (Btu/lb)	7288	7084	7043	6975	7156	7084
Proximate Analysis (wt%)						
Ash	3.88	3.88	3.97	4.00	3.26	4.05
Volatile	35.56	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	7.81	8.09	7.07	8.11
Hydrogen	5.61	5.43	5.64	5.62	5.28	5.80
Nitrogen	1.58	1.02	1.82	1.88	1.63	2.19
Sulfur	0.82	0.85	0.88	0.72	0.73	0.88
Ash Composition						
SiO ₂	48.50	52.80	42.80	47.80	49.60	44.80
Al ₂ O ₃	29.20	28.00	28.50	27.03	25.10	22.80
Fe ₂ O ₃	15.00	8.65	17.50	15.01	11.80	18.90
CaO	1.74	2.32	1.57	2.53	2.40	3.00
MgO	0.58	0.57	0.59	0.55	0.60	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	1.80	0.80
TiO ₂	1.45	1.20	1.13	1.15	0.80	1.30
MnO ₂	0.05		0.04			
P ₂ O ₅	0.51	0.19	<0.08	0.26	0.20	0.30
V ₂ O ₅	0.04		0.08			
PbO	<0.12		<0.12			
Ash Fusion Temperature (°F)						
Oxidizing/Reducing						
Initial Deformation	2385/2415	2485/2375	2480/2150	2645/2450	2560/2205	2480/2144
Softening	2650/2475	+2700/2700+	2620/2180	+2700/2480	2650/2285	2681/2345
Hemispherical	2690/2515	+2700/2700+	2630/2300	+2700/2560	2670/2325	2688/2419
Fluid	2700/2605	+2700/2700+	2680/2580	+2700/2595	2687/2632	2678/2491

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	54.38
Ash Content (wt%)	2.15	2.19	1.97	2.07	1.85
Particle Content					
% Passing 100 micron			98.83		
% Passing 74 micron		98.95	98.81	98.77	98.79
% Passing 45 micron	99.60	99.43	98.70	99.08	98.83
% Passing 37 micron	99.90	99.03	98.29	98.51	98.18
% Passing 25 micron	98.00	91.80	93.45	97.91	94.88
% Passing 15 micron	85.80	80.15	88.48	75.18	75.08
% Passing 8 micron	50.40	59.70	39.20	41.08	41.04
% Passing 4 micron	36.40	41.86	28.12	29.42	29.35
% Passing 3 micron	28.00	34.45	19.34	22.88	22.30
% Passing 2 micron	18.00	23.98	12.84	15.37	14.85
% Passing 1 micron	3.50	10.82	3.58	5.39	4.48
Mean Size (micron)	8.00	7.80	12.80	10.40	10.87
Slurry Viscosity (cp)					
@ 100/sec	300.00	300	310	150	275
@ 1000/sec	400.00	340	178	180	300
Slurry (Btu/lb)	7013	6888	6841	7174	7238
Proximate Analysis (wt%)					
Ash	3.93	4.05	3.84	3.80	3.01
Volatiles	38.01	38.78	37.32	34.82	34.88
Fixed Carbon	58.08	57.17	58.84	61.28	62.41
Ultimate Analysis					
Carbon	82.23	81.30	82.32	84.09	84.40
Oxygen	8.85	8.83	11.51	7.88	7.78
Hydrogen	5.88	5.81	3.88	5.58	5.53
Nitrogen	1.80	1.82	1.85	1.78	1.88
Sulfur	1.44	1.84	0.43	0.82	0.81
Ash Composition					
SiO ₂	50.80	48.02	52.04	48.49	42.58
Al ₂ O ₃	23.10	28.38	31.73	28.31	28.58
Fe ₂ O ₃	13.80	18.75	8.2	12.00	13.80
CaO	2.70	1.88	2.9	4.18	5.17
MgO	0.01	0.58	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	0.88	0.85
TiO ₂	1.30	1.14	1.18	1.09	1.03
MnO ₂					
P ₂ O ₅	0.20	0.23	0.88	0.16	0.14
V ₂ O ₅					
PbO					
Ash Fusion Temperature (°F)					
Oxidizing/Reducing					
Initial Deformation	2837/2070	2548/2389	+2700/2602	2872/2367	2422/2287
Softening	2700/2180	2858/2447	+2700/2695	2894/2419	2840/2355
Hemispherical	2700/2270	2885/2483	+2700/2700+	+2700/2487	2884/2425
Fluid	2700/2474	2873/2488	+2700/2700+	+2700/2651	2880/2467

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