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

**Final Report
June 1986 - April 1994**

R. T. LeCren

May 1994

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

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

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

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ABBREVIATIONS

AMAX	Amax Research & Development Center
CFGT	Coal-Fueled Gas Turbine
CSC	Component Screening Combustor
CWM	Coal-Water Mixture
CWS	Coal-Water Slurry
DCFGT	Direct Coal Fired Gas Turbine
HESR	Hot End Simulation Rig
IBSTF	Integrated Bench Scale Test Facility
PFC	Pressurized Fluidized Bed Facility
PRIS	Particulate Removal Impact Separator
TSSC	Two-Stage Slagging Combustor
$\Delta P/P$	pressure drop per pressure
MMBtu	Million British Thermal Units (based on Lower Heating Value)
msec	millisecond
P_{in}	Inlet air pressure
pph	pounds per hour
ppmv	parts per million by volume
pps	pounds per second
psig	pounds per square inch gauge
T_{in}	inlet air temperature
T_{outlet}	secondary combustor outlet temperature
T_{out}	secondary combustor outlet temperature
T_{pz}	primary zone temperature
wt%	percent by weight

SECTION 1

INTRODUCTION

Demonstration of a direct coal-fueled gas turbine system that is environmentally, technically, and economically viable depends on the satisfactory resolution of several key issues. Solar's technical approach to these issues was to advance a complete direct coal-fueled gas turbine system that incorporated near-term technology solutions to both historically demonstrated problem areas such as deposition, erosion, and hot end corrosion, and to the emergent environmental constraints based on NO_x, SO_x, and particulates. Solar's program approach was keyed to the full commercialization of the coal-fueled cogeneration gas turbine which would occur after extended field verification demonstrations conducted by the private sector.

The program was structured in three phases plus an optional fourth phase:

- **Phase I - System Description**

A preliminary definition phase was conducted during which continuing market studies hardened the target market economic and siting constraints and a preliminary commercialization plan was detailed. The target market data were used as input to the preliminary definition of the commercial cogeneration gas turbine system -- performance goals, operational characteristics, and conceptual subsystem designs. The information, in turn, led to the formation of a comprehensive component development plan.

- **Phase II - Component Development**

The second program phase entailed bench-scale and full-size component and subsystem development and preparation. Emphasis was placed on the generation of full-size component performance data in addition to information relevant to scaling to larger size gas turbines. Components and subsystems were initially sized for the Centaur Type 'H' gas turbine. The development activities were guided by the Phase I plan and included combustor development; cleanup development; fuel specification development; a hot end simulation rig test; and system modeling. The major "go/no-go" decision points were contained within Phase II. The first occurred before the start of high-pressure testing; the second was to have occurred at the completion of the phase.

- **Phase III - Prototype System Verification**

The final program phase was to integrate the full-size component hardware into a full engine system and conduct an extended verification test run on coal fuel. Performance data are generated during the test run and from post-test disassembly and analysis including gaseous and particulate emissions, system efficiency and power output, and transient response characteristics. A market assessment was to be done to enable the decision to be made whether or not to carryout the Phase IV field evaluation.

- **Phase IV - Field Evaluation**

An optional phase was to have been added to the program. Realizing that the 100 hour test in Phase III would only prove the concept, a longer field evaluation under industrial cogeneration operating environment was to be accomplished to identify operational problems. The implementation of this phase depended on a successful proof-of-concept test and a favorable market assessment.

SECTION 2

DISCUSSION

2.1 PHASE I - SYSTEM DESCRIPTION

The activity in Phase I was reported in a topical report (Solar SR87-R-5278-15). The major areas were: system goals and design constraints, system description, fuel specification, market studies, economic evaluation, commercialization and preparation of a research and development plan (Solar SR87-R-5278-13).

The results from the Phase I activity are as follows:

The preliminary market survey evaluated potential applications for the Centaur Type H coal-fueled gas turbine system. Based on these market studies a CFGT system definition was developed. This system definition reflected both market and technology-imposed constraints. Subsystem requirements and performance goals that addressed the Centaur Type H engine requirements, and future environmental standards that were expected to be applicable to the system, were incorporated into the system definition. Coal fuel specifications suitable for the CFGT were established, and the implications of coal fuel type and degree of coal cleaning were evaluated from a technology and economic standpoints. Preliminary system designs and component configurations that reflect the use of coal fuels were established. Based on these studies, the following conclusions were drawn:

- The Centaur Type H Coal Fueled Gas Turbine was technically viable. The Phase I evaluations identified a number of technology voids that needed to be addressed for the CFGT system to be commercially successful. Based on these issues, a Phase II (Component Development) R&D Plan was generated to address these needs.
- The market studies identified three main applications where early acceptance for the coal-fueled Centaur Type H gas turbine seemed likely. These markets were industrial cogeneration, enhanced oil recovery, and military base applications. The site survey showed that the markets for industrial cogeneration were potentially large and geographically broad. The enhanced oil recovery markets were clustered in a few regions. The targeted military base applications, on the other hand, will be dispersed throughout the U.S.; it is possible that "third parties" would be involved in operating these cogeneration facilities. The market for the 2 to 10 MWe cogeneration plant was improving relative to larger systems due to a developing economic drive (utilities buy back rates are becoming much lower) which will forced cogeneration plants to match their outputs to their plant load requirements. There were at least six areas in the U.S. which could have potentially become CFGT cluster sites. The six areas were Chicago, Philadelphia, Pittsburgh, Houston, Los Angeles, and San Francisco. These areas would have been able to utilize and support a centralized coal fuel processing plants with capacities in the range 14.6 to 35 MWe. Such a central coal fuel preparation plant would drastically lower the fuel cost.

- The economic viability of the Centaur Type H coal-fueled system is directly related to the cost of both the coal fuel and the competitive fuels/systems in those market sectors identified for earliest penetration. Analysis of competitive fuels/systems showed that the coal-fueled Centaur could be economically attractive immediately upon commercial introduction in those market sectors where premium liquid-fueled systems were then in use.
- Two potential types of coal fuel for the Centaur Type H gas turbine system were assessed; coal-water mixture (CWM) and dry pulverized coal. A technical evaluation of the two fuels showed that there were additional issues associated with the use of dry pulverized coal over and above those for CWM. These included reduced combustor efficiency, higher NO_x emissions, and reliable operation of a high pressure feed system. In addition, potential safety and health hazards are associated with the production, storage, and handling of pulverized coals that impacted the projections of site fuel costs for the Centaur Type H system. Comparing on-site preparation of dry coal to that of CWM showed that the fuel cost for "minimum-cleaned" dry pulverized coal would be closely comparable to a similar grade of CWM. As a result of these assessments it was concluded that a CWM would be the more appropriate fuel for use in the Centaur type H and that the Phase II R&D Plan should reflect this relative level of interest in the two coal fuel types.

2.2 PHASE II - COMPONENT DEVELOPMENT

There were four major tasks in Phase II: combustor development, particulate removal system development, coal fuel specification development and hot end simulation rig. Topical reports on each have been issued. The coal fuel specification work is covered in a topical report from the subcontractor, AMAX, and in the combustor development topical report.

The results of this phase provided the design data required to fabricate the full scale combustor and PRIS which was used to conduct preliminary tests prior to being incorporated in the Phase III proof-of-concept engine test. Sufficient information was generated to write the procurement specification for the ceramic barrier filter to be used between the combustor island and the turbine section of the engine.

As an overview, the combustion system consists of a Two-Stage Slagging Combustor (TSSC), a Particulate Rejection Impact Separator (PRIS), and a Secondary Filter arranged as shown in Figure 1. The TSSC is a rich-lean staged combustor designed for NO_x control. Air and fuel are introduced in the primary zone and additional air is added in the secondary zone. The primary zone is operated fuel rich (equivalence ratio of 1.38) with an outlet temperature of 2900°F and the secondary zone operates fuel lean (equivalence ratio of 0.4) with an outlet temperature of 1900°F. All components in the combustion system are refractory lined. Coal ash is removed aerodynamically in the slagging primary zone and in the PRIS which is situated in the rich zone between the primary and secondary combustion zones. In both ash removal locations, inertial separation is used to remove 90 to 95 percent of the ash. The secondary filter is a high temperature barrier filter designed to remove the remaining ash and sulfur sorbents.

Figure 1. System Description

2.2.1 Combustor Development

(Reference Topical Report SR94-R-5278-133)

The objectives of this task were to complete the subscale development testing and to design, fabricate and test the full scale combustion system. The combustor program started with a design configuration derived during the Component Screening Combustor (CSC) program. The design went through the following evolution: CSC design which had some known shortcomings, redesigned CSC now designated the TSSC, improved TSSC with the PRIS evaluated in the Integrated Bench Scale Test Facility (IBSTF), and full scale design. Supporting and complimentary activities included computer modelling, flow visualization, slag removal, SO_x removal and fuel properties evaluation.

2.2.1.1 Combustor Design

The two shortcomings of the CSC combustor were: 1, slag would flow up the outer walls and escape into the secondary thus reducing the slag capture in the primary and increasing the load on the PRIS when it was inserted between the primary and secondary zones; and 2, some unburnt fuel was escaping from a secondary recirculation zone, which would only partially burn in the secondary zone reducing combustion efficiency. Both problem areas were attacked by designing alternate primary zone configurations. These designs were arrived at with the assistance of computer modelling and flow visualization. The initial and final configurations are shown in Figure 2. As can be observed the major changes were to increase the length above the injectors and to angle the outer walls. Increasing the height above the injectors reduced the slag carryover because the slag was not accelerated into the transition to the secondary. The escape of unburnt fuel was reduced because there was now volume above the injectors where the fuel in the secondary recirculation could react before exiting the primary zone. This problem was further reduced with the incorporation of the PRIS in later tests because it provided additional time at primary zone temperature so that this fuel could react.

Figure 2. Initial and Final TSSC Configurations

The full size combustor was designed based on a scale-up of the TSSC configuration as tested in the IBSTF. The design effort aided was by a full size flow visualization model. The full scale combustor was selected, detailed and fabricated. The combustor, shown in Figure 3, featured four CWM injectors and a batch slag pit. The selection of a four injector design over a single injector design was as a result of subscale combustor testing, full scale flow visualization, and atomization studies of full scale injector hardware.

The four injector full scale combustor primary zone design includes elements that proved 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 1. The distance the injectors penetrate into the primary zone was

Figure 3. Full-Scale Combustor

Table 1. 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

narrowed through flow visualization studies, so that two distances could be studied in combustion testing. The primary zone was cast with three types of refractory material to minimize heat loss through the casing. In the subscale combustor only two materials were used. The primary zone was expected to perform as well or better than the subscale combustor and did.

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

The secondary combustor was scaled directly from the subscale model. Table 2 compares the geometries of the full and subscale designs. Both designs featured six air inlet ports angled at 37° from the combustor centerline. The secondary zone was refractory lined with two materials to minimize heat loss.

Table 2. Secondary Zone Scaling

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

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

2.2.1.2 Modelling

2.2.1.2.1 Computer

A computer program called INTERN was used to analyze the alternate primary zone configurations that were proposed as solutions for the problems with the CSC combustor. The fact that the fuel was injected from the back wall toward the dome was a problem for the modelers since this was not

the conventional arrangement. This difficulty was overcome and valuable runs were made which indicated possible configuration changes.

2.2.1.2.2 Flow visualization

To verify and evaluate the computer modelling results a flow visualization task was initiated. Models of the candidate configurations were fabricated from Plexiglass. A narrow slit light source was installed in the impact dome. By injecting neutral density helium filled soap bubbles into the air the primary zone flow patterns could be observed and assessed. High speed photography and video were utilized to document the observations for comparison with other configurations. The slag carryover was evaluated by injecting a viscous fluid with a viscosity similar to the slag. By measuring the fluid collected in the slag tap and comparing it with the amount injected, a slag capture number could be computed.

2.2.1.3 Slag Removal

Design and testing of two water quenched slag pits for continuous slag removal was completed. The purpose of 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 featured a water bath and a lock hopper valve to the side of the pit. The purpose of this design was to evaluate a simple lock hopping arrangement for continual slag removal. Testing continued to improve slag tap heating to ensure slag flow into the water bath. The lock hopper valve was operated multiple times while burning CWM with no negative impact on the system. The lock hopper design showed promise as a method for slag removal. This design was intended to be incorporated into the full size design.

2.2.1.4 Testing

Three combustor rigs were utilized: the TSSC, the IBSTF and the full scale rig at Peoria. The TSSC rig, which was 1/10th scale of the proposed system, consisted of a primary and secondary zone and was used to develop the primary zone performance and to evaluate SO_x and slag removal and fuel properties variations. The IBSTF rig which included all the components of the proposed system was also 1/10th scale except for the particulate removal system which was about 1/30th scale. This rig was used to verify combustor performance data obtained on the TSSC, to develop the PRIS and the particulate removal system. The full scale rig initially included the primary and secondary zones and was later modified to incorporate the PRIS.

2.2.1.4.1 TSSC

This rig was used for a variety of tasks. These included:

- Evaluation of the redesigns of the CSC combustor from the previous program
- Evaluation of SO_x reducing sorbents
- Development of the slag pit configuration and slag removal scheme
- Evaluation of a water-cooled impactor

- A series of CWM's possessing different properties have been formulated and evaluated in ten combustion tests. The properties that have been studied include coal loading, ash concentration, particle size, CWM additives, and several coal seams.
- Evaluation of CWM prepared on site

During this program the TSSC rig was operated for approximately 75 hours and burned 42,000 pounds of CWM.

2.2.1.4.2 IBSTF

As stated above this rig included all the components of the proposed system. The main purposes were to test and develop the PRIS and the Ceramic Barrier Secondary Filter. Nine test series were run, the first three were shakedown of the facility, the next four were devoted to developing the PRIS and the last two concentrated on the Secondary Filter.

2.2.1.4.3 Full Scale

Work was initiated at the Caterpillar Technical Center for testing the full scale combustor at pressures up to 7.8 atmospheres. Accomplishments included selection of a test site, definition of various subsystems required for testing, shipment of the combustor hardware, and design of the test site installations. CWM combustion was accomplished for the first time in Test No. 4. The combustor operated stably on CWM reaching anticipated outlet temperatures. The back pressure valve was undersized resulting in a lowering $\Delta P/P$ as the test proceeded. The flow split was below design at 2.3. Two more tests were completed of the full scale combustor without the PRIS in-line island. Data for all full scale testing with CWM is included in Table 3 and in Figure 4.

Test Nos. 5 and 6 were completed to further characterize the performance of the combustor in terms of emissions, outlet temperature versus flow split, combustion efficiency, and slag removal. Test No. 7 was the initial test of the complete combustor Test No. 5 was completed after the combustor flow split of primary to secondary air flow rate had been adjusted. A larger back pressure valve than used in Test 4 allowed greater control so that the combustor $\Delta P/P$ could be maintained near 4 percent throughout the test. As indicated in Table 3 and included in Figure 4 the average secondary combustor outlet temperature reached 1811°F and the primary combustor outlet temperature reached 2995°F, before that thermocouple failed. The test was completed without any difficulties.

Post-test inspection was completed with a borescope following the test revealed that the refractory was in fair shape at all locations except directly above the impactor on the primary walls. At this location a band of 6 to 12 inches high over about one third the circumference had been damaged and broken revealing white unslagged refractory. The depth of the pocket where refractory broke free could not be readily determined with the borescope, but was estimated to be between 0.5 and 3.0 inches. The total thickness of the inner-most casting (Kaocrete HPM 90) is 3.0 inches. The impactor appeared to be in excellent shape along with the refractory surrounding the injectors. The slag tap was blocked entirely with frozen slag indicating two possibilities: (1) that a piece of the refractory that had broken from the primary wall blocked the hole and was subsequently covered with slag or (2) the region beneath the impactor at the slag tap was too cool and the slag froze before dripping off the slag tap. Temperature measurements made beneath the impactor indicate levels above 2450°F. These measurements are made one inch inside the refractory at the ribs. The secondary combustor contained a considerable amount of frozen slag and ash.

Table 3. Test Conditions and Results for Full Scale Combustor

Test No.	Design Goals*	4	5	6	7
Date	--	5-23-91	9-4-91	9-26-91	3-11-92
CWM (variation)	--	'W'	'W'	'X'	'X'
T _{in} (°F)	620	605	607	618	627
P _{in} (psig)	126	61.5	71.0	74.0	102.1
Φ _{primary}	1.38	1.33	1.06	1.23	1.27
ΔP/P (%)	4	3.7 to 3.2	3.9	3.8	4
Heat Input (MMBtu/hr)	68	44.8	40.1	46.5	48.0†
T _{outlet} (°F)	1900	1967	1811	1905	1292
Split	2.80	2.75	2.68	2.73	3.00
Results					
CWM Used (lbs)	--	13,960	25,240	17,017	2446
Test Duration (hrs)	--	2.20	4.13	2.58	0.30
Emissions @ 15% O₂					
NO _x (ppmv) [lbm/MMBtu]	<125	52.1 [0.245]	73.9 [0.321]	64.7 [0.297]	95.7
CO (ppmv) [lbm/MMBtu]	<50	31.4 [0.044]	50.9 [0.134]	13.1 [0.037]	3.1
SO ₂ (ppmv) [lbm/MMBtu] (without sorbent)	<75 [Sorbent]	171.0 [171.0]	181.0 [1.112]	194.0 [1.243]	N/A
Particulate (ppmv)	<120	N/A	N/A	N/A	N/A
Carbon Conversion (%)	>98	N/A	N/A	N/A	N/A
Primary Zone Slag Capture (%)	>70	N/A	N/A	N/A	N/A
*From outstanding performance ranking.					
†15% of total fuel input was due to DF #2.					

The emissions were measured in six points. NO_x data are included in Figure 4 versus equivalence ratio. A considerable discrepancy existed between the calculated primary zone equivalence ratio based on measured air/fuel flow rates and measured O₂ concentrations. Historically, a difference of approximately 5 to 7 percent has existed for subscale tests. In this test the difference has approached 15 percent. The equivalence ratio shown in Figure 4 are based on the measured O₂ concentration. Regardless of which equivalence ratio is used both indicate that the NO_x emissions are acceptably low. The data also indicate that the equivalence ratio was consistently low throughout the test. The major reason the test was run at below normal stoichiometries is that the coal had settled in the tank to some extent reducing the coal loading to 51.3 wt% rather than 54.1 percent. During the test it was the fuel flow rate was set based on the 54.1 percent loading to yield an equivalence ratio above 1.3, but because of the reduced loading the equivalence ratio was

Figure 4. Full Size Combustor Test Results

consistently low. The CO emissions were slightly higher than in Test 4 with an average of 50.9 ppmv.

Test 6 was completed approximately three weeks following Test 5. A new batch of CWM "X" had been delivered with similar characteristics to the CWM "W" used in the previous tests. The combustor remained in the same shape as at the conclusion of Test 5 (i.e., with the slag tap blocked and a piece of the refractory broken off the primary zone wall).

The test conditions and a summary of results for this test are included in Table 3. The test was completed at similar conditions as Test 5. The primary zone equivalence ratio was maintained closer to 1.3 than in Test 5, but was still low at 1.23. A CWM sample taken during the test indicated the coal loading was approximately 54.1 percent. During the test the primary zone refractory temperatures reached 2837° F and the secondary combustor outlet temperature reached 1905° F. A particulate sample taken during the test was found to result in a clogged probe. The emission probes failed during the after only one data point was taken. The problem is believed to be that cooling water to one probe was shut-off, which resulted in no cooling water reaching any of the three probes. This occurred because of the cooling water piping configuration and the low pressure "tower" water supply used. Corrections for this problem are being implemented. The test was terminated after operating 2.6 hours on CWM when two "hot-spots" developed on the casing. The cause of these hot-spots are presumed to be refractory failure, but this has not been confirmed. Emissions data and temperature data for Test 6 versus equivalence ratio are included in Figure 4. Only one emissions point was recorded before the emission probes failed. Again, the emissions are within acceptable limits.

Test 7 was the first test with the PRIS in line. A typical air heat-up was followed for approximately 2 hours before lighting the diesel torch. Air heater and fuel control problems were encountered which delayed lighting of the injectors. Once on diesel, a 4-5 hour heating schedule was followed. About 3 hours into the heat-up 3 primary zone thermocouples were lost. This occurred at an average temperature of 2200°F in this area. Diesel continued until the PRIS elbow thermocouple was lost and a leak in a primary zone weld was discovered. The run was subsequently terminated. The primary zone and elbow thermocouple breakdowns were due to internal thermocouple wire failures. The outer protection tube and inner wire sheaths were intact and reusable. New thermocouple sheaths and wires were replaced inside existing protection tubes for the retest, Test No. 7b, scheduled for the next day. A smaller 3.8 in. diameter plate, used to adjust the flow split, was also installed in the primary air leg for the retest due to the low flow split experienced.

The secondary elbow thermocouple was found to be cracked and was replaced prior to the retest. A 3 to 4 hour, abbreviated diesel heating schedule was followed since operating temperatures were rapidly achieved prior to fuel switching. The combustor had a hard light when starting the diesel. During the run, monitoring pressure data was difficult due to condensation in the transducer lines which affected data readouts. During the middle of the diesel heat-up, the ΔP across the PRIS was observed to drop from 1 to 1.2 percent to 0 percent. Whether this drop was due to a faulty reading or a failure of the PRIS rods is unknown. PRIS elbow and inlet thermocouples were lost during the heat-up. The PRIS elbow thermocouple was replaced with one from the primary zone since the failure was due to broken wires. The PRIS inlet thermocouple has a potted terminal block inside the protection tube and was unable to be repaired. Change-over conditions were maintained for approximately an hour while emissions and air heater difficulties were managed. At this point primary zone temperatures were 2700 to 2800°F, with an improved air split of 2.8 to 3.1. A decision was made to run on CWM for as long as the PRIS elbow thermocouple provided reliable data. However, approximately 25 minutes on CWM, a water quench solenoid was lost, and fuel flow became very unstable, almost going down to zero. Diesel was ignited and the CWM flow turned down. Soon thereafter, a primary zone thermocouple was lost along with the DAS. Primary zone temperatures were noted at 3036°F prior to the failure. A serious leak developed in the secondary elbow thermocouple prompting a rapid shutdown procedure.

Major achievements of the full scale testing are:

- Four tests using CWM completed for a total of over 9 hours (approximately 59,000 pounds of CWM burned).
- Initial test of full size PRIS completed.
- Performance of the full size combustor correlated with subscale data.

2.2.1.5 Crude Oil Evaluation

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

In Test 1 the rig was smoothly changed over to crude, and ran for approximately 50 minutes before a leak formed in the primary zone causing rapid shutdown. Attempting to run a range of fuel flows to characterize the combustor on crude, it was discovered that the fuel delivery system did not respond well at low flows. Several data points were taken with equivalence ratio ranging, on the rich side, from 1.58 to 1.83. Primary zone temperatures were approximately 2600°F, while transition zone

temperatures were around 1900° F. The secondary combustion zone remained cool throughout the test running between 600 to 800° F.

Post-test inspection revealed a melted primary zone. Most of the refractory had flowed down the side walls, at some points exposing only the outer steel skin. The refractory settled in the impactor section, although the impactor was still visible and in excellent condition. It appears that some reaction took place between the coal-slag coated refractory and the crude effluent, because the impactor did survive and was used in Test 2.

Looking at the injector section, some degradation of the outer sleeve of one of the injectors was found. A new conical piece was fabricated and rewelded to the sleeve. The reason for this rupture is not known. The remaining injectors were in good condition.

New primary, secondary, and transition zones were fabricated and testing continued. The diesel start was very smooth. It was not necessary to get the refractory walls up to the usual 2400° F, as required for CWM, therefore, the switch to crude oil was performed 2 hours into the heat-up. The switch went very smoothly as temperatures quickly increased. The equivalence ratio was varied as much as possible and emission points were taken. Since this was the first test using the effervescent atomizer, the air assist was also varied to observe any effect on combustor performance.

While varying equivalence ratio, primary zone wall temperatures ranged from 2443 to 2662° F, while secondary outlet temperatures ranged from 1417 to 2052° F. In light of extraordinarily high crude oil pump pressures, above the 600 psig maximum of the gauge, rig pressure was decreased to 60 psig in order to continue the test at near design conditions. Emissions were typical, operating in O₂ ranges of 13.2 to 16.4%. Given the high temperatures and limited fuel and rig pressure ranges, approximately 375 pounds of crude oil was burned.

Preliminary inspection revealed clean, intact walls, impactor section, and residence section. However, the face of one injector, which was removed for inspection, was badly burnt, stripping away the primary air weld around the annulus. The relative success of this second test verifies the claim that crude oil can be run in the TSSC.

2.2.1.6 Fuel Injector Development

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.

An alternate fuel injector approach called effervescent injection was studied under subcontract to Purdue University. The predicted advantages were a reduction in the amount of air assist flow required and reduced sensitivity to viscosity variations. The Purdue work is described in their final report listed in the references. At Solar a set of effervescent injectors was built and tested in the TSSC during the crude oil evaluation described in Section 2.2.1.5.

2.2.1.7 SO₂ Removal

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.

2.2.1.8 Fuels

A series of tests were conducted to assess the impact of different slurry properties on combustor performance. The fuels tested were similar in most ways to previously tested fuels with the exception of stabilizer being omitted from one. The absence of stabilizer was observed to retard slag capture and create periods of temperature fluctuations. The properties that have been studied included coal loading, ash concentration, particle size, CWM additives, and several coal seams.

2.2.2 Particulate Removal System Development (Reference Topical Report SR94-R-5278-132)

This task ultimately included two components, the PRIS and the ceramic barrier filter system between the combustor island and the turbine section of the engine. Since the predicted ash removal of the primary zone of the TSSC was 60 to 70 percent it was deemed necessary to incorporate a device between the primary and secondary zones to increase the removal efficiency. Based on previous data obtained from a contract with the Pittsburgh Energy Technology Center (Contract No. DE-AC22-83PC60418) on impact separators the PRIS was designed and tested. In contrast to the configuration tested in the PETC contract, which consisted of a plate with an array of holes followed by an impact plate on which the jets impinged, the PRIS consisted of rows of staggered cylindrical rods. The space between the rods in one row served as the restriction to generate a jet which impinged on the rod in the next row. Combining the effects of the primary zone and the PRIS the ash removal exceeded 90 percent of the mineral matter in the fuel.

The ceramic barrier filter was developed for two reasons; (1), even with over 90 percent ash removal in combustor island the particulate levels would have been above acceptable levels for turbine life; and (2), if a sulfur sorbent was used the resulting particulate had to be removed.

Several particulate rejection technologies were examined. These included high efficiency cyclones ceramic bag filters, ceramic crossflow filters, electrostatic precipitators, granular bed filters, impact separators, and ceramic candle filters. Only one technology, the ceramic candle filter, was tested. Two types of candle filters were tested, both of silicon carbide construction. These filters were tested in a subscale facility that operated at approximately 1 to 1.5 pps.

The first series of tests were conducted using a silicon carbide filter manufactured by Schumacher of West Germany. These filters were of the same variety tested at the Grimethorpe pressurized fluidized bed facility (PFC). Some of these candle filters failed with low service lives. A second candle filter, manufactured by Refraction for Industrial Filter and Pump Manufacturing Company, was tested with some mixed success. Failures were experienced with these candles as well, but they appeared more promising than the Schumacher candles.

2.2.3 Coal Fuel Specification Development

The bulk of this task was done by AMAX under a subcontract from Solar. Their work included process development, production cost estimates, surveys of available coals and their properties, analysis of slag samples, supply of CWM for testing and development of a computer to predict the slagging characteristics in a rich primary zone combustor. The AMAX effort is documented in a series of reports. Work at Solar included; a series of tests on the TSSC using fuels with variations

in properties, additive packages and particle size, the results of which were used to establish a CWM specification and a feasibility study of on-site slurry preparation. The effort at Solar is included in the Combustor Development Topical Report.

2.2.4 Hot End Simulation Rig

(Reference Topical Report SR94-R-5278-128)

Because it was realized early in the program that the 100 hour proof-of-concept test in Phase III would not generate significant data on effects of the products of coal combustion on turbine materials and coatings it was proposed to build a subscale rig which would subject samples of typical turbine materials and coatings to the coal combustion environment. Test durations of 1000 and 5000 hours were envisaged.

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

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Long-term rig reliability has been improved. A conical primary zone and impactor section was developed and tested to allow for slag accumulation during 250 hour tests. A candle filter shroud protected the element from direct impingement of particulate, which previously led to blinding of the candle. A flexible candle mount system had been established and was proven successful during extended testing. Supplemental heating of the material sample section was modified and demonstrated effectively. Still recommendations were needed to ensure rig longevity.

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

2.3 PHASE III - PROTOTYPE SYSTEM VERIFICATION

The purpose of this phase was to demonstrate the technical and environmental feasibility of a direct coal-fired gas turbine by running a Centaur Type H generator set for 100 hours burning a coal water slurry fuel. The installation was to include all the components required to prepare the slurry, remove the ash, control the sulfur dioxide emissions and remove the particulate matter resulting from carryover ash and spent sorbent. The plan was to utilize the full size combustor rig installed and tested at the Caterpillar Tech Center in Peoria, Illinois during Phase II. The standard Centaur Type H engine had to be modified to provide the capability for routing the compressor discharge air to the offsite combustor island and then returning the hot gases to the turbine section. One component in the system was a turbine inlet scroll which would see temperatures of approximately 1925° F. As an expedient for this test and to provide a means of controlling the radial temperature profile into the turbine it was decided to design and fabricate a steam-cooled scroll. This task was completed before the program was redirected.

Another decision that was made concerning the conduct of the proof-of-concept test was that the coal-water slurry would be prepared on-site. At the time that the engine test was scheduled there was only one viable source of CWS, AMAX located near Denver, Colorado. If the CWS was to be supplied by AMAX, either a large storage tank would have had to be installed at the Tech Center or a large fleet of tanker trucks assembled. Neither was deemed viable. As reported in Phase II a pilot test was conducted to determine the feasibility of on-site CWS preparation. The conclusion was positive, so the required equipment was identified.

2.4 PHASE IV - FIELD EVALUATION

It was realized at one point in the program that the 100 hour test conducted in Phase III would provide only minimal data concerning the commercialization of a direct-coal fired gas turbine. Therefore a fourth phase was discussed and proposed which would include an extended field test at a site representative of a gas turbine cogeneration application. Although this phase was never incorporated into the program some preliminary work was done to find a site and additional funding. One of the candidate sites was the Caterpillar Tech Center. There were already three diesel engine generator sets and there was a need for steam which was being supplied by an adjacent Caterpillar facility. An economic study indicated that a one year demonstration using coal followed by conversion of the equipment to natural gas was feasible. Because of the redirection of the program this Phase was not pursued any further.

SECTION 3

CONCLUSIONS

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

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

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

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

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

SECTION 4

RECOMMENDATIONS

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

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

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

Although the PRIS aerodynamic performance exceeded predictions the rod material performance was not satisfactory. Rod material and installation must be studied.

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

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