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

**Annual Report
2 June 1992 through 1 June 1993**

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

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June 1993

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ABBREVIATIONS AND SYMBOLS

AFR	Advanced Fuel Research
ALR	Air to Liquid Ratio
AMAX	Amax Research & Development Center
ATS	Advanced Turbine System
BYU	Brigham Young University
CFDRC	CFD Research Corporation
CWM	Coal-Water Mixture
DCFT	Direct Coal Fired Turbine
EDX	Energy Dispersive X-Ray
IBSTF	Integrated Bench Scale Test Facility
PRIS	Particulate Removal Impact Separator
SEM	Scanning Electron Microscopy
SMD	Sauter Mean Diameter
TSSC	Two Stage Slagging Combustor
XRD	X-Ray Diffraction
cp	centipoise
P_{in}	inlet air pressure
ppb	parts per billion
ppbw	parts per billion by weight
pph	pounds per hour
ppm	parts per million
ppmm	parts per million by mass
ppmv	parts per million by volume
ppmw	parts per million by weight
psi	pounds per square inch
psid	pounds per square inch differential
psig	pounds per square inch gauge
T_{in}	inlet air temperature
T_m	melting point, absolute temperature
tpy	tons per year
T_{outlet}	secondary combustor outlet temperature
μm	micron

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

1.0 INTRODUCTION

This program was initiated in June of 1986 because advances in coal-fueled gas turbine technology over the previous few years, together with DOE-METC sponsored studies, served to provide new optimism that the problems demonstrated in the past can be economically resolved and that the coal-fueled gas turbine could ultimately be the preferred system in appropriate market application sectors. In early 1991 it became evident that a combination of low natural gas prices, stringent emission limits of the Clean Air Act and concerns for CO₂ emissions made the direct coal-fueled gas turbine less attractive. In late 1991 it was decided not to complete this program as planned.

The objective of the Solar/METC program was 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. Component development of the coal-fueled combustor island and cleanup system while not complete indicated that the planned engine test was feasible. Preliminary designs of the engine hardware and installation were partially completed.

The original five-year program consisted of three phases, namely:

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

A successful conclusion to the program would have initiated a continuation of the commercialization plan through extended field demonstration runs. After notification of the intent not to complete the program a replan was carried out to finish the program in an orderly fashion within the framework of the contract. A contract modification added the first phase of the Advanced Turbine Study whose objective is to develop high efficiency, natural gas fueled gas turbine technology.

The specific tasks to be completed to bring the contract to an orderly and beneficial conclusion were identified. The task breakdown was as follows:

- Task 1 - Phase II Carryover
- Task 2 - Scroll Design
- Task 3 - Full Size Combustor Test
- Task 4 - IBSTF Candle Test
- Task 5 - Market Study
- Task 6 - TSSC Crude Test
- Task 7 - Fuel Injector
- Task 8 - Advanced Turbine Study
- Task 9 - Computational Fluid Dynamic Modelling
- Task 10 - Reporting
- Task 11 - Pulse Combustor

2.0 SUMMARY

This report covers the activity during the period from 2 June 1992 to 1 June 1993.

To date Solar has demonstrated:

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

During the past year the following items were completed:

- Some of the candle filters which had been exposed for approximately 30 hours in the IBSTF were analyzed by Acurex. Their report has been issued to METC.
- Initial testing of the subscale TSSC burning crude oil was completed.
- Investigation of the effervescent fuel injector was nearly completed at Purdue. With development of a focused image holography system the near nozzle breakup mechanism was studied with some unexpected results.
- Phase I of the Advanced Turbine System program was completed and the final report issued.
- CFD modelling of the TSSC was carried out by AFR and BYU using the PCGC-2 code. The final report is in preparation.
- CFD modelling at CFDRC began with the goal of studying spray combustion.

3.0 TASK 1 - PHASE II CARRYOVER

3.1 SPECIFIC ITEMS OF PROGRESS

- Task completed.

3.2 DISCUSSION

This was an effort to complete Task II activities, primarily the AMAX subcontract. The task was completed in the previous reporting period (Ref. 1).

4.0 TASK 2 - SCROLL TEST

4.1 SPECIFIC ITEMS OF PROGRESS

- Task completed, report issued

4.2 DISCUSSION

As part of Phase III a steam-cooled turbine inlet scroll design was started. The purpose of this task was to complete the design and stress analysis. The initial design is completed, the drawings have been released and a report of the design and analysis has been issued.

5.0 TASK 3 - FULL SIZE COMBUSTOR TEST

5.1 SPECIFIC ITEMS OF PROGRESS

- Testing was completed in the last reporting period (Ref. 1).
- Dismantling of rig and refurbishment of test area was completed.

5.2 DISCUSSION

As of 12-31-91 the full size combustor had been tested at the Caterpillar Tech Center. The testing incorporated the primary and secondary zones but not the PRIS. It was proposed to continue the full size combustor test program by running one more test incorporating the PRIS for an assessment of its performance. This test was run but very little data were obtained because of refractory failures which probably caused a failure of the PRIS rods. See Reference 1 for details. After a review of the status in light of the phasing out of the program, it was decided to cease testing, dismantle the rig and refurbish the test area.

6.0 TASK 4 - IBSTF CANDLE TEST

6.1 SPECIFIC ITEMS OF PROGRESS

- The IBSTF was completely dismantled including the exhaust system.
- Discussions were held with John Sawyer of Acurex regarding post-exposure testing.
- Ceramic coupon samples that were exposed during the candle test in the IBSTF were shipped to Acurex for analysis.
- Candles were shipped to Acurex for analysis under their METC contract.
- C Ring, SEM and XRD tests were completed.
- Analysis of the test results on the candles at Acurex was completed, report was submitted to METC.

6.2 DISCUSSION

Discussions were held with John Sawyer of Acurex Corporation regarding post-exposure testing of the Refractron candle filters, both 505 and 442-T bonds.

The proposed testing included:

C-Ring Testing of the Refractron Candles

In this test, 6 rings from each of three candles will be tested under tension and compression at room temperature and at high temperature. Both types of candles will be tested (Refractron 505 and 452-T) for a total of 72 c-rings prior to exposure and 72 c-rings after exposure.

SEM/EDX

Acurex Environmental will use SEM/EDX to determine if there has been any surface effects due to exposure of the ceramic candles. To accomplish this, the SEM/EDX analyses of three new 505 and three new 442-T candles will be compared to the SEM/EDX analyses of three exposed 505 and 442-T candles.

XRD

Three samples each of new 505 and 442-T candles will be analyzed by X-ray diffraction. The diffraction patterns of exposed candles will be compared to the diffraction patterns for the new candles to determine any crystallinity or phase changes which may be the result of exposure.

Ceramic coupon samples were sent to Solar by Acurex for exposure in the IBSTF. Since that testing has been completed the samples were returned to Acurex for analysis.

Acurex analyzed twelve candle filters, six unexposed and six exposed, under their DOE contract. There were two different binders used in the Refractron candles. The analysis/testing was completed and a report prepared. It was submitted by Acurex to the METC program manager with a copy to Solar.

7.0 TASK 5 - MARKET STUDY

7.1 SPECIFIC ITEMS OF PROGRESS

- Deleted from program

7.2 DISCUSSION

A market study was done in Phase I but that was 6 years ago. For a coal-fueled gas turbine to be economically viable it needs to handle low grade fuels other than coal. It also seems that a world-wide market rather than just the United States has to be considered. Therefore, it was proposed to update the previous study expanding it to consider present conditions, other low grade fuels, and a world-wide market. This task was deleted because of insufficient funding.

8.0 TASK 6 - TSSC CRUDE TEST

8.1 SPECIFIC ITEMS OF PROGRESS

- Completed first test of the TSSC on crude oil.
- Status of rig hardware reviewed and quotes for recasting obtained.
- Recasting of rig hardware was completed.

8.2 DISCUSSION

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. A test was proposed using the TSSC and a crude oil from California's San Joaquin Valley to verify the claim.

The first test of the TSSC on crude oil was performed. In order for the crude to flow easily through the delivery piping, barrel heaters were used to heat the fuel prior to the injectors. A typical fuel temperature of 165°F was maintained. Diesel #2 was used as a pilot fuel to heat the rig. The time on pilot fuel was substantially shorter compared to burning CWM, because of the lower ignition temperature for crude. Only 2.6 hours were spent on the heating of the rig prior to fuel changeover.

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. While 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 1.58-1.83. 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 600-800°F. Several emissions points were taken and are listed in Table 1.

**Table 1. Emission Data From TSSC Crude Oil Test.
Corrected to 15% O₂.**

Data Point	Fuel	CO (ppm)	NOx (ppm)	HC (ppm)	O ₂ (%)
1	DF#2	16.9	43.3	26.3	18.48
2	DF#2	20.3	47.4	21.2	18.22
3	Crude	9.2	72.0	0.1	14.66
4	Crude	5.7	132.3	N/A	14.43
5	Crude	4.0	79.5	N/A	13.29

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 will be used in the next run. An ash fusion temperature analysis of the crude oil will be done. It is thought that the slag may melt at a lower temperature than expected and may have caused the refractory failure.

Looking at the injector section, some degradation of the outer sleeve of one of the injectors was found. Figure 1 shows the injector section after the crude oil test. Shown in Figure 2. is the injector with a small hole on the side near the weld. A new conical piece will be fabricated and rewelded to the sleeve. The reason for this rupture is not known. The remaining injectors were in good condition.

Figure 1. Primary Injector Section After the TSSC Crude Oil Test

Figure 2. Hole Near Weld on Primary Zone Injector

9.0 TASK 7 - FUEL INJECTOR

9.1 SPECIFIC ITEMS OF PROGRESS

- A prototype set of injectors was fabricated based on dimensions provided by Purdue.
- The prototype set of injectors were flowed to determine the primary orifice effective area and the drop sizes generated at atmospheric pressure with water.
- At Purdue a new holographic system was set up to better image the spray.
- Purdue researchers continued to make adjustments to the holographic system before drop sizing was initiated.
- Problems of optical noise generation caused by very small drops immediately downstream of the nozzle were solved and the holographic process fine tuned.
- Holograms were made with the revised system with the objective of studying ligament breakup with fluids having different viscosities.
- Investigations of the effects of surface tension on the transition zone structure were completed.
- Focused image holograms of the spray were made using fluids with and without polymers which simulate the stabilizers used in Coal-water slurries. These holograms showed that the spray breakup without polymers is different than originally postulated and that the addition of polymers changes the spray breakup characteristics.

9.2 DISCUSSION

One shortcoming of the present fuel injector is that a significant amount of high pressure air assist flow is required. The effervescent injector approach under study by Purdue promised to reduce the flow requirement. This work was authorized during the previous reporting period and it was proposed to continue it to its planned conclusion.

A prototype set of 4 injectors was fabricated. The design of this set was done by Solar using parameters supplied by Purdue. Evaluation of the spray characteristics was planned using flow test benches. The injectors were first installed on the air flow bench which is used to determine the effective area of the primary orifices for each of the four injectors.

Injector No. 1 was installed on the atmospheric atomization bench to evaluate the spray generated with a laser diffraction drop sizing instrument. Measurements were made with water as the fuel. Figure 3 is a graph of the data obtained with that injector compared to the baseline TSSC injector. As the graph clearly illustrates the effervescent injector produces comparable drop sizes as the baseline does at one-tenth the air assist flow rate. The required air assist pressure to produce sprays with similar drop sizes with the two injector designs was approximately 5 times as great with the effervescent injector as with the baseline. The other observation made during atomization testing is that the effervescent atomizer produced larger satellite drops at the spray periphery. These drops are produced by the primary air which acts to coalesce some of the drops.

Figure 3. Comparison of Baseline TSSC Injector With Effervescent Atomizer at Atmospheric Pressure Using Water

Figure 3 suggests that smaller drop sizes are produced with the effervescent injector operating at higher fuel flow rates. This result is contrary to expectations and measurements made at Purdue. One significant difference between the injector tested at Purdue and the prototype injector is the addition of primary air supply on the prototype. Evaluations of the other three prototype injectors will be completed to confirm this.

The initial in-line hologram system did not produce the images desired, so an off-axis system was designed, built, and tested that allows satisfactory images.

Work continued to adjust and refine the holographic system. Overheating of the ruby laser became a problem which hampered testing. A cooling system was devised so that extensive spray holography could be initiated.

Attempts to take holograms of the effervescent injector while flowing water were not satisfactory because of optical noise generated by very small drops immediately downstream of the nozzle. There was some other noise caused by two lenses in the construction system. These lenses were replaced. Then holograms were taken with higher viscosity fluids. It was found that the structure of the liquid in the transition zone of an effervescent atomizer is very dependent on the amount of air used to atomize the liquid into drops.

The investigation of the transition zone of an effervescent atomizer was continued via focused-image holography. The focus of this work was two-fold: 1) to study the effect of changes in viscosity on the structure of the effervescent spray, and 2) to establish a technique that will enable the viewing of the two phase shock/expansion prevalent in high mass flow rate effervescent atomizers in order to observe its effect on the atomization process. It was found that viscosity has an effect on the air-liquid ratio at which the transition zone changes.

The investigation of the effects of surface tension on the transition zone structure was accomplished. The main conclusion is that as the surface tension is decreased the ligament diameter decreases as does the mean diameter size. The explanation for this behavior is continuing since it disagrees with some previous work.

Focused image holograms were made for various fluids with and without polymers. Without polymers the main conclusion is that the near nozzle break up mechanism is primarily governed by the breakup of a sheath of liquid by rapidly expanding bubbles (bubbly flow regime) or a cylindrical sheet of liquid by high relative velocity expanding air (tree regime). The transition between these regimes occurs at air-to-liquid ratios (ALR) of approximately 5%. A plot of ALR vs Drop size shows a knee in the curve where the transition occurs, see Figure 4. Increasing the ALR above the transition value does not improve atomization significantly. If a polymer is added then the breakup is inhibited such that the transition does not occur and in fact ligaments don't readily form. Figure 5 is an artist's sketch of two break up regimes.

This work is scheduled to be completed and a draft final report submitted by the end of June 1993.

SMD vs. ALR at Liquid Mass Flow Rate of 5 g/s

Figure 4. ALR vs Drop Size

ALR = 0.02

ALR = 0.10

Figure 5. Newtonian vs Non-Newtonian Spray Breakup

10.0 TASK 8 - ADVANCED TURBINE STUDY

10.1 SPECIFIC ITEMS OF PROGRESS

- Completed Phase I study and issued Topical Report (Ref. 1).

10.2 DISCUSSION

This was an added task requested by METC. This task was authorized by Modification A025 to the contract dated June 4, 1992.

Solar Turbines Incorporated intends to both support and participate in the Advanced Turbine System (ATS) program developed by the Department of Energy (DOE). As part of this involvement Solar intends to design and commercialize a unique gas turbine system that promises high cycle efficiencies and low exhaust emissions. This engine of approximately 12-MW will be targeted for the dispersed power markets both urban and rural.

The goals of the program were developed based on surveys of customers future needs and on estimates of what levels might be demanded for future exhaust emissions. Goals of 50% thermal efficiency and 8 parts-per-million by volume (ppmv) nitrogen oxide emissions were established. While these goals are challenging, Solar is confident that they can be met. Reliability, availability, and maintainability (RAM) will continue to be the most important factors in the competitive marketplace. A goal of improving or at least maintaining RAM equal to that provided by today's engines was therefore adopted. The other major goal adopted was one of reducing the cost of power produced by 10%. This reduction is based on the cost of power (COP) associated with today's engines that lie in the same horsepower range as that targeted in this study.

An advanced cycle based on an approximation of the Ericsson Cycle was adopted after careful studies of a number of different cycles. This advanced intercooled, recuperated engine when fired at 2450°F will be capable of meeting the 50% efficiency goal if the cooling air requirements do not exceed 7% of the total air flow rate. This latter qualification will probably dictate the use of ceramic parts for both the nozzle guide vanes and the turbine blades. Cooling of these parts will probably be required and the 7% cooling flow allowance is thought to be adequate for such materials. Analyses of the cost of power and RAM goals show that the installed cost of this advanced engine can be approximately 50% above today's costs. This cost is based on \$4.00 per million Btu fuel and a COP reduction of 10% while maintaining the same RAM as today's engines.

11.0 TASK 9 - CFD MODELLING

11.1 SPECIFIC ITEMS OF PROGRESS

- Sent full size combustor dimensions and description to Advanced Fuel Research and BYU.
- Work was concentrated in the following areas: coal to char chemistry, fundamental high pressure reaction rate data, large char particle oxidation, SO_x/NO_x submodel development, integration of submodels into the entrained-flow code and application of the generalized code.
- Energy balance problems encountered for particle combustion with radiation were resolved.
- The work began at CFDRC and was concentrated on spray combustion modeling and Solar combustion analysis.
- Work continued at CFDRC and was concentrated on premix chamber modeling, spray combustion modeling, NO_x modeling and chemical kinetics.

11.2 DISCUSSION

Development time for gas turbine combustion systems, particularly those for low grade fuels like coal, could be reduced if working computer models were available. Solar has been working with CFDRC on conventional combustor and fuels for low NO_x applications. It was proposed that we have them continue work they have been doing for Solar to develop liquid spray combustion models and NO_x models for prompt and fuel bound nitrogen NO_x . Additionally the METC COTR directed Solar to contact Advanced Fuel Research to have the Solar combustor modelled by them using the BYU code (PCGC-2).

AFR/BYU

The first step was for Solar to provide combustor definition and test results to AFR and BYU. Dimensions and a description of the full size combustor as tested at the Caterpillar Tech Center were sent to AFR and BYU. A summary of representative test data was prepared.

Work continued on developing code graphics and preparing the user's manual. The final versions of the pre- and post-processors were completed. A draft copy of the user's manual was prepared for review. Work continued with PCGC-2 to resolve a question with the energy balance. Several minor problems were resolved in the code and an energy balance was achieved for particle combustion with radiation, where it is suspected that a significant change in the code will be needed. It was reported that the energy balance issue appeared to be resolved. Subsequent work indicated that some questions still remained. Although the balance was greatly improved from what it was before, it still did

not close as tightly as it should, and the investigation continued. In the meantime, work continued with the cold flow simulation of the primary zone. Previous issues with the convergence associated with the interior inlet were resolved, and a converged cold flow gas solution was achieved. Work then commenced on a cold flow simulation with particles. Several new issues were raised with the particles interacting with intrusions and with the wall. Most of these issues appear to have been resolved, and a converged cold flow simulation with particles was achieved. Work was then initiated on the reacting flow simulation.

CFDRC

A contract was let to CFD Research Corporation to examine how to obtain low NO_x while burning liquids (crudes and residuals and CWM). This work is intended to complete the study of the TSSC and to support subsequent phases of the ATS programs.

Work at CFDRC was started. Customization of previous spray combustion research by CFDRC to gas turbine combustion chambers was started. Modeling of diesel sprays is in progress.

Effort was concentrated on trying to make a lean premixed swirler model converge with some success using the latest code. Because the capability of adequately modeling droplet entrainment in combustion recirculation zones additional refinement of the code was undertaken. Some success was achieved. Work began on refinement of the NO_x and chemical kinetics models.

12.0 TASK 10 - REPORTING

This is an administrative task with no technical implications.

13.0 TASK 11 - PULSE COMBUSTOR

13.1 SPECIFIC ITEMS OF PROGRESS

- Testing completed, final report in preparation.

13.2 DISCUSSION

The purpose of this task was to complete the work started on another contract to evaluate the suitability of a coal-burning pulse combustor for gas turbine applications. The tests were completed and the final report was prepared.

During this program, high pressure operation of a pulse combustor was achieved on both natural gas and pulverized coal. Stable operation of the pulse combustor was achieved with natural gas at pressures up to 85 psig. The measured NO_x concentrations were nearly independent of the system pressure. No pressure boost due the pulse combustion operation was measured during the natural gas testing.

The coal combustion tests were performed at approximately 1/4 of the designed firing rate due to limitations on the mass flow through the ceramic barrier filter. Stable operation of the pulse combustor with only pulverized coal firing was not achieved. Approximately 40% natural gas support was required to maintain pulsations in the pulse combustor.

The refractory lined pulse combustor showed significant deterioration during the combustion testing. Large cracks (about 1/4 inch wide) were present in the upper portions of the refractory lining of the combustor. The insulating refractory lining next to the combustor shell became powdered and plugged the static and dynamic pressure ports during many of the tests. Castable refractory is not a suitable material for high pressure pulse combustors.

REFERENCES

1. Annual Report - 2 June 1991-1 June 1993 SR92-R-5278-105
2. Topical Report - Advanced Turbine System - Phase I SR93-R-5278-115

END

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