Advanced Turbine Systems Program Conceptual Design and Product Development

**Quarterly Report
February - April 1995**

K. W. Karstensen

July 1995

Work Performed Under Contract No.: DE-AC21-93MC30246

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

By
Solar Turbines Incorporated
San Diego, California

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EXECUTIVE SUMMARY

This Quarterly Technical Progress Report covers the period February 1, 1995, through April 30, 1995, for Phase II of the Advanced Turbine Systems (ATS) Program by Solar Turbines Incorporated under DOE contract No. DE-AC21-93MC30246. The objective of Phase II of the ATS Program is to provide the conceptual design and product development plan for an ultra high efficiency, environmentally superior and cost competitive industrial gas turbine system to be commercialized by the year 2000. A secondary objective is to begin early development of technologies critical to the success of ATS.

Tasks 1, 2, 3, 5, 6 and 7 of Phase II have been completed in prior quarters. Their results have been discussed in the applicable quarterly reports and in their respective topical reports. With the exception of Task 7, final editions of these topical reports have been submitted to the DOE. This quarterly report, then, addresses only Task 4 and the nine subtasks included in Task 8, "Design and Test of Critical Components." These nine subtasks address six ATS technologies as follows:

- Catalytic Combustion - Subtasks 8.2 and 8.5
- Recuperator - Subtasks 8.1 and 8.7
- Autothermal Fuel Reformer - Subtask 8.3
- High Temperature Turbine Disc - Subtask 8.4
- Advanced Control System (MMI) - Subtask 8.6
- Ceramic Materials - Subtasks 8.8 and 8.9

Major technological achievements from Task 8 efforts during the quarter are as follows:

- The subscale catalytic combustion rig in Subtask 8.2 is operating consistently at 3 ppmv of NOx over a range of ATS operating conditions.
- The spray cast process used to produce the rim section of the high temperature turbine disc of Subtask 8.4 offers additional and unplanned spin-off opportunities for low cost manufacture of certain gas turbine parts.

On February 23, amendment M004 to the contract was issued to extend the period of performance from November 30, 1995 to May 30, 1996. The purpose of this no-added-cost extension was to accommodate minor changes in a subcontractor's statement of work which delayed the start of work. Beginning with the March monthly report, performance has been reported against the Labor and Cost Plans included with the Management Plan submitted in connection with amendment M004.

Contract labor and cost status as of April 30, 1995:

Labor: 21,206 hours versus 22,448 planned.

Total Program Cost*: \$2570K versus \$3155K planned.

*Including Solar's cost share.

9249 labor hours have been charged to an internally funded project directly related to ATS. This represents cost sharing of approximately \$833,000 in addition to that provided for in the contract.

1.0 WORK STATUS

Tasks 1,2,3,5,6 and 7 have been completed and topical reports submitted for each, with the exception of Task 7. The Task 7 topical report is in final review at Solar and will be submitted early in the next quarter.

1.1 TASK 4 - CONVERSION TO COAL

Task 4 of ATS, Phase, II, requires the definition of a system to convert the gas-fueled advanced turbine system (GFATS) to a coal-fired advanced turbine system (CFATS). Start of work on this task was delayed until near-final cycle conditions for the GFATS defined in Task 3 as well as for interim systems defined in Tasks 5, 6, and 7 became available. Now that the definition of a GFATS in Task 6 has been completed Task 4 work resumes.

Four approaches to handling both coal- and biomass-derived gaseous fuels have been identified:

- Direct Firing
- Pressurized Fluidized Bed Combustion (PFBC)
- Gasification
- Direct Firing

Direct coal firing has been the subject of work at Solar under contract to DOE-METC over the past ten years. Experience gained from this work has been applied in evaluating direct coal firing for ATS. PFBC and indirect firing both present major control challenges during engine start-up and load changes due to the large air volumes involved. Gasification appears to be the most practical approach for use with a modified ATS combustion system.

Costing of the infrastructure required for all four systems has been started. It is expected that these analyses will support the choice of gasification as the appropriate CFATS conversion scheme. The work will then conclude with an economic analysis of coal as an alternative fuel to natural gas in Solar's advanced turbine system.

1.2 TASK 8 - DESIGN AND TEST OF CRITICAL COMPONENTS

During this quarter, work progressed on all nine of the Task 8 Subtasks as reported in the following discussion.

1.2.1 Subtask 8.1 - Low Pressure Drop Recuperator

Subtask 8.1 has three objectives:

- To measure performance of the ATS recuperator core over the range of ATS operating conditions.
- To determine the basic heat transfer and flow loss characteristics of the ATS recuperator heat transfer surface.

- To validate analytical methods employed to predict core creep life.

The first two objectives were addressed by testing on steady state and transient recuperator rigs at the Caterpillar Technical Center near Peoria, IL. The third involves measurement of creep strain in an internally pressurized, flattened tube specimen which simulates the folded fin configuration of the ATS primary surface recuperator (PSR). This flattened tube test rig is located at Solar's development test facility in San Diego. All work on the first two objectives is complete and has been reported in the Task 8.1 Topical Report now in internal review. The remaining effort on the third objective involves a continuing long term creep test. This continuing work will be transferred to Subtask 8.7 - Recuperator Materials with final report coverage in the topical report for Subtask 8.7.

Performance testing of the ATS recuperator core model was accomplished at The Caterpillar Technical Center on the steady state performance rig shown in Figure 1. Using a 12-inch core sample, this rig measures steady state heat transfer effectiveness and static pressure loss at actual engine operating conditions of temperature and pressure. Testing at a total of 35 ATS gas turbine operating points was completed in the prior quarter and during this quarter these test results were analyzed and compared with predicted recuperator performance. A topical report covering Subtask 8.1 will show that measured performance of the ATS recuperator core is in full support of estimated data used in calculating ATS gas turbine performance in Task 6. This rig was also used to obtain thermal transient characteristics of the core. These results will be a key input to modelling the dynamic response of the recuperated ATS gas turbine.

Figure 1.

Steady State Performance Test Rig

The transient test rig is used to obtain pressure drop and thermal response data. These parameters are used in the design, analysis and prediction of performance of recuperators. In order to improve the accuracy of the data used in various computer models of performance, it was decided to run an air-side only surface, a

gas-side only surface and a combined air and gas side surface. All three surfaces have been manufactured. The air and gas surfaces were assembled and delivered to Caterpillar. The combined surface will be assembled and delivered shortly. The rig has been extensively calibrated using standard heat transfer cores. These cores have been used over the years to ensure validity and integrity of the rig. The most recent tests show excellent agreement, both with and without the thermal attenuator which was added recently to the rig. An uncertainty analysis has also been performed and it reveals an uncertainty exists of about eight percent in heat transfer performance data but only three percent in pressure/friction data. At typical NTUs (Number of Transfer Units, see Glossary), a 12 percent change in heat transfer performance data will cause a one percent change in effectiveness.

Figure 2.

Transient Performance Test Rig

The results of the tests on each core are shown in Tables 1, 2 and 3 (surfaces 90, 91, and 92, respectively). The high capacity surface, which will be used in the recuperator for the ATS program, was tested for both gas side, air side and combined surfaces (cores 90, 91 and 92, respectively). These empirical data are needed in the design, analysis and prediction of performance of primary surface recuperators. It is clear there is quite a difference between the air and gas sides, especially at the higher Reynolds numbers. This potentially could result in higher accuracy predictions of performance.

Results from the transient rig testing will also be reported in the Subtask 8.1 topical report. The resulting heat transfer surface characteristic data will also be incorporated into Solar's 2D analytical model in order to sharpen the model's ability to predict recuperator performance.

Creep evaluation, the third objective, is conducted using a flattened tube to simulate a scaled-up cross section of the recuperator primary surface folded profile. The scale-up is necessary in order to provide a test article of sufficient size to attach strain gages. A room temperature pressure test shows that strain measurements are in good agreement with an ANSYS finite element model at pressures below 200 psi – the normal range of operation of ATS recuperators (Figure 3). The test work has advanced into the high temperature creep test stage and has progressed past the point of strain gage saturation. From that point forward, creep strain is being measured by dimensional measurements of the tube itself.

As of the end of the quarter just past, the flattened tube test rig has operated 1896 hours of testing of a Type 347 stainless steel specimen plus another 456 hours on a Haynes Alloy 230. Type 347 is the recuperator sheet alloy used in all primary surface recuperator production to date at Solar and will be used initially in ATS. Haynes 230 is one of several alloys with increased temperature capability which are candidates for future ATS improvements.

In order to allow timely publication of the Subtask 8.1 topical report dealing primarily with recuperator performance issues, the continuing flattened tube test work will be moved to Subtask 8.7 which deals with recuperator materials. This will have no effect on the distribution of planned labor and costs between these two subtasks.

1.2.2 Subtask 8.2 - Subscale Catalytic Combustion Rig

This task was formerly titled "Low Pattern Factor Combustor" and had as its objective the reduction of combustor outlet temperature pattern factor to a level compatible with very high average temperature levels. Revision A003 to the contract added Subtask 8.5, originally titled "Low

Table 1. Transient Performance Data for Core 90 (Gas-side).

Quantity	Run #1	Run #2	Run #3	Run #4	Run #5	Run #6
$P_{\text{barometric}}$, in-Hg	29.62	29.62	29.62	29.63	30.07	29.64
$T_{\text{db, ambient}}$, °F	72.32	72.32	72.5	72.32	72.66	72.68
$\Delta P_{\text{cold, orifice}}$, in H ₂ O	5.36	2.145	11.62	6.02	1.36	1.69
$P_{\text{cold, orifice, inr}}$, in H ₂ O	-1.825	-0.875	-3.4	-0.4	-0.125	-4.8
$\Delta P_{\text{cold, core}}$, in H ₂ O	0.925	0.465	1.65	0.205	0.085	2.31
$P_{\text{cold, core, inr}}$, in H ₂ O	-0.8	-0.38	-1.575	-0.15	-0.04	-2.325
$T_{\text{cold, core, inr}}$, °F	71.69	71.69	72.14	71.57	72.74	72.26
$T_{\text{cold, orifice, inr}}$, °F	72.68	73.04	72.77	73.31	73.58	72.68
$\Delta P_{\text{hot, orifice}}$, in H ₂ O	5.41	2.15	11.76	6	1.27	1.73
$P_{\text{hot, orifice, inr}}$, in H ₂ O	-1.85	-0.85	-3.4	-0.4	-0.12	-4.9
$T_{\text{hot, core, inr}}$, °F	92.9	92.72	92.24	93.86	94.4	92.18
$T_{\text{hot, orifice, inr}}$, °F	87.08	86.72	88.16	85.64	83.84	88.16
t , avg lapse sec	8.388	11.856	6.164	18.286	32.144	5.095

Table 2. Transient Performance Data for Core 91 (Air-side).

Quantity	Run #1	Run #2	Run #3	Run #4	Run #5	Run #6
$P_{\text{barometric}}$, in-Hg	29.72	29.37	29.32	29.3	29.28	29.27
$T_{\text{db, ambient}}$, °F	72.86	71.96	72.32	72.5	70.34	70.52
$\Delta P_{\text{cold, orifice}}$, in H ₂ O	3.915	11.675	5.16	16.67	3.045	6.075
$P_{\text{cold, orifice, in}}$, in H ₂ O	-0.775	-1.525	-3.45	-7.575	-12.6	-21.6
$\Delta P_{\text{cold, core}}$, in H ₂ O	0.67	1.21	2.575	5.22	8.38	13.88
$P_{\text{cold, core, in}}$, in H ₂ O	-0.095	-0.25	-0.775	-2.165	-3.8	-6.975
$T_{\text{cold, core, in}}$, °F	72.86	71.87	72.23	72.23	69.89	70.66
$T_{\text{cold, orifice, in}}$, °F	73.58	73.04	72.59	72.5	70.43	70.88
$\Delta P_{\text{hot, orifice}}$, in H ₂ O	3.93	11.78	5.22	16.66	3.04	5.99
$P_{\text{hot, orifice, in}}$, in H ₂ O	-0.8	-1.55	-3.5	-7.7	-12.8	-21.6
$T_{\text{hot, core, in}}$, °F	91.1	92.84	92.12	91.76	91.46	90.27
$T_{\text{hot, orifice, in}}$, °F	83.84	84.74	85.82	87.44	87.08	86.9
$t_{\text{avg tapes}}$, sec	28.4	17.4	11	7.46	5.78	4.4

Table 3. Transient Performance Data for Core #92 (combined air/gas).

Quantity	Run #1	Run #2	Run #3	Run #4	Run #5	Run #6
$P_{\text{barometric}}, \text{in-Hg}$	29.67	29.67	29.67	29.66	29.68	29.65
$T_{\text{db, ambient}}, ^\circ\text{F}$	73.31	73.85	72.59	72.95	72.68	72.68
$\Delta P_{\text{cold, orifice}}, \text{in H}_2\text{O}$	3.88	16.795	5.85	14.625	2.84	4.45
$P_{\text{cold, orifice, in}}, \text{in H}_2\text{O}$	-0.37	-1	-2.29	-4.61	-8.25	-11.775
$\Delta P_{\text{cold, core}}, \text{in H}_2\text{O}$	0.22	0.59	1.315	2.5	4.21	5.83
$P_{\text{cold, core, in}}, \text{in H}_2\text{O}$	-0.09	-0.32	-0.85	-1.9	-3.6	-5.35
$T_{\text{cold, core, in}}, ^\circ\text{F}$	73.64	73.79	72.2	72.32	72.47	72.32
$T_{\text{cold, orifice, in}}, ^\circ\text{F}$	74.21	74.48	72.77	72.68	72.68	72.23
$\Delta P_{\text{hot, orifice}}, \text{in H}_2\text{O}$	3.96	16.92	5.94	14.71	2.86	4.46
$P_{\text{hot, orifice, in}}, \text{in H}_2\text{O}$	-0.35	-1.05	-2.3	-4.65	-8.3	-11.8
$T_{\text{hot, core, in}}, ^\circ\text{F}$	92.42	91.82	91.46	90.92	91.28	90.56
$T_{\text{hot, orifice, in}}, ^\circ\text{F}$	82.76	85.28	86.72	86.9	87.44	87.08
$t, \text{avg lapse sec}$	29.8	17.5	11.16	7.73	5.81	4.88

Figure 3. Flattened Tube Tests and FEM Strain Comparison at Room Temperature

Emissions Combustor." Both subtasks are now addressing the development of very low emission and low pattern factor catalytic combustion for Solar's ATS. Subtask 8.5 is now titled "Full Scale Catalytic Combustion Rig," and will feature a single full-scale ATS combustor can.

At the close of the last reporting period, unsatisfactory performance of the subscale catalytic combustor with the longer (10.5 inch) bed was attributed to an unacceptable catalyst inlet velocity profile.

Measurements of the velocity profile of gases entering the catalyst have been completed for several premixer configurations to improve the profile. A five-hole pitot probe was traversed directly upstream of the catalyst bed in two radial directions. These tests were completed at ambient conditions (atmospheric pressure and 70°F). Results, included in Figure 4, are plotted as velocity versus position across the catalyst inlet cross-section. On this plot, 2 inches corresponds to the flow path centerline. The baseline configuration shown as "Position A" has been used in all recent combustion testing. This configuration yielded a +44 percent peak-average variation in the flow field. The goal is a +10 percent peak-average variation.

Three modifications to the premixer to flatten the catalyst inlet profile have been tested. Results are shown in Figure 4.

- 1) The first configuration changes the baseline by replacing the 3 - 4 inch premixer diffuser with a constant 3 inch diameter premixer duct from the venturi to the catalyst bed (designated as "3 inch Diameter Flow Path" in Figure 4).

Figure 4. Catalyst Inlet Velocity Profiles

Figure 5. Subscale Catalytic Combustor Test Rig Configured to Flatten Catalyst Inlet Velocity Profile

- 2) The configuration labelled "Center Venturi Premixer Blocked" has a one inch diameter rod mounted along the centerline from the venturi outlet to the exit of the catalyst bed. This rod completely blocks the center venturi.
- 3) The final configuration is an extension of 2), above, which has been modified by including a 1.5 inch flow straightener upstream of the catalyst bed. This configuration is illustrated in Figure 5.

The data shown in Figure 4 indicates that all these configurations flattened the profile but the arrangement of Figure 5 provided the flattest profile at +11 percent peak-average. Based on these results, the combustor rig was modified to reflect the changes illustrated in Figure 5. Combustion testing with this configuration has been completed.

This configuration was tested for both fuel profile and combustion performance. This design has provided the flattest velocity profile entering the catalyst bed at +11 percent peak-to-average. This fuel profile was measured and optimized to ± 6.7 percent peak-to-peak.

A series of combustion tests were conducted over a three day period, yielding the best results to date. The combustor was operated for over 2 hours without any auxiliary fuel burning downstream of the catalyst bed with rig pressure at 120 psig. The system operated in a stable manner over a range of inlet temperatures from 770°F to 900°F and a variation in fuel/air ratio from 4 to 3.7 percent (volume). The NO_x emissions were consistently below 3 ppmv (corrected to 15 percent O₂). CO and HC emissions, however, were as high as 1000 ppmv of CO and 250 ppmv of HC. Some of the "cleaner" data is plotted in Figure 6. Here CO is near 100 ppmv and HC below 60 ppmv.

On post-test inspection the bed was found to be in good condition except for a 1 square inch circle where the bed was deformed and some of the material was missing. The cause of this failure was

Test 80, 4/25/95; 120 psig, 60 fps, 900°F

Figure 6. Catalytic Combustor Results

a hot spot – bed temperature exceeding 2500°F – that developed during testing at the higher fuel/air ratios. Catalyst supplier Engelhard is completing the analysis of the used bed.

A catalyst bed with the same design is being prepared for more testing. The volume of the post-catalyst combustor will be increased by enlarging the flow diameter from 4 inches to 6 inches.

This volume change will increase the residence time from 9 msec to 20 msec. This is expected to improve the burn-out of CO. The optimum CO burnout will occur at residence times of 35 msec. Modifications to increase the residence time toward this target are being designed. Testing with the 6 inch diameter flow path will be completed during May.

1.2.3 Subtask 8.3 - Autothermal Fuel Reactor (ATR)

Autothermal fuel reformation consists in reacting a hydrocarbon fuel such as natural gas (methane) with steam in order to produce a "reformed" fuel with a high hydrogen content – on the order of 70 percent or greater. Since hydrogen burns in leaner mixtures and at lower temperatures than other fuels, this "reformed fuel" will produce inherently lower NO_x emissions. In an ATS, a combustor can with a built-in ATR has the potential of very low emissions. In addition, ATRs can be designed for use with a wide variety of alternate fuels – coal- and biomass-derived gaseous fuels, for example – and can also increase gas turbine efficiency when the steam required for the process is produced with recovered exhaust heat. Solar's ATR project was begun using a tube reactor as shown in Figure 7. This rig has been used to establish the basic characteristics of the process and, further,

Figure 7.

Tube Reactor for Reforming Catalyst Screening Tests

to address several durability issues such as catalyst life and the effect of certain acidic compounds (H_2S , HCl , for example) often found in raw natural gas. These results were reported in the previous quarter. The tube reactor is now being modified in anticipation of future work on diesel fuel and coal- and biomass-derived fuels.

Fabrication of the modified ATR test rig is nearing completion. Ceramic monoliths coated by nickel reforming catalyst with lanthanum as a promoter were received from the supplier and rig testing will be resumed.

Tests using the ATR batch-tube reactor on the reformation of liquid (diesel) fuel have confirmed the production of over 60 percent hydrogen in the product stream. The product gas ignition can be achieved without torch assistance at temperatures of approximately 800°F. The ignition energy of the hydrogen rich gas is much less than that of natural gas—a major factor in making low temperature catalytic combustion possible.

Next, attempts were made to compare the ignition behavior of reformer product streams using the ATS batch-tube reactor. Temperature readouts monitored by thermocouples are illustrated in Figure 8 where a controlled air flow was introduced downstream of the reformer to burn the product gas. As shown, the product streams with hydrogen above 37 percent were ignited easily without torch assistance with both diesel fuel and natural gas as the feedstock. Under the same conditions natural gas heated through the tube reactor without reforming raised the temperatures only about 100F. This low ignition energy requirement is one of the benefits for reformation of conventional fuels to produce hydrogen rich gas for combustion in a gas turbine.

The ATR test rig has been reassembled and installed at the existing test facility after modification. The testing is designed to evaluate the combustion efficiency, emission levels, pressure drop, operating range and flame temperature. Stability of combustion of the hydrogen-rich product gas and any tendency toward flashback will also be monitored during the test.

1.2.4 Subtask 8.4 - Dual Property Turbine Disc

The objective of this subtask is to provide Solar's ATS with a turbine disc with improved high temperature creep strength in the rim portion while maintaining current levels of low cycle fatigue (LCF) strength/life at the hub. Improving the high temperature creep strength of the rim portion contributes to gas turbine thermal efficiency by reducing the requirements for cooling air bleed flow. This technology can also be applied to Solar's current and future non-ATS product.

The approach selected by Solar and subcontractor Howmet is to produce the rim element by spray-casting MAR-M-247 alloy and the hub from Udimet 720 powder alloy. Consolidation of both materials will be by hot isostatic pressing (HIPing). HIPing will also be applied to achieve a solid-to-solid bond between the two elements.

	A	B	C	D
FUEL	N. Gas	N. Gas	N. Gas	Diesel
STEAM	yes	yes	yes	yes
REFORMER	no	partial	yes	yes
GAS STREAM COMPOSITION (after heated tube-reactor): (dry, vol%)				
H2	3.36	37.11	62.55	62.14
CH4	90.66	49.28	13.78	5.64
CO	1.43	5.15	22.21	22.82
CO2	1.60	8.46	1.46	9.17
C2+	2.95	-	-	0.23

Figure 8. Temperature Readouts Monitored by Thermocouples

During this quarter, subscale (3- 9- and 13-inch diameter) rim elements have been successfully spray cast, HIPed and heat treated. Microstructure evaluation has been completed and mechanical properties testing is underway. First article Udimet 720 hubs will arrive early in the next quarter and bonding trials will begin.

In addition to the spin-off potential of the dual alloy turbine disc technology into Solar's non-ATS product, successful spray casting of the rim alloy has identified further spin-off potential in the manufacture of gas turbine parts. Application of spray casting to ring-shaped gas turbine parts in high temperature alloys can provide one or more of the following:

- Parts which cost less than those made from ring forgings.
- Parts from "unforgeable" alloys
- Parts from alloys providing creep-rupture strength not obtainable in forged alloys.

1.2.5 Subtask 8.5 - Full-Scale, Single Can Catalytic Combustor Rig

This subtask was added by Revision A003 to the contract and was originally titled "Low Emissions Combustor." As part of an overall catalytic combustor project along with Subtask 8.2 It is now defined as catalytic combustor development using a full ATS-scale, single can rig.

The basic design of this rig was completed in the previous quarter and placed on hold during much of the quarter just past. The hold was put in place to allow for the detail design to accommodate changes indicated by the subscale rig test work of Subtask 8.2. Primarily these changes relate to obtaining a satisfactory catalyst inlet velocity profile and to providing sufficient post-catalyst volume to enable more complete CO burn out.

1.2.6 Subtask 8.6 - Total Plant Controls

During the quarter covered by this report design specification for the ATS MMI (Man-Machine Interface) was completed. Work continued throughout the quarter on the following long-term elements:

- The Application Programming Interface for the GMS (Graphical Modelling System) graphical user interface.
- Automatic configuration and embedding routines.
- Diagnostic and security routines.
- The Graphical User Interface (GUI).
- ETHERNET and ICN data acquisition command modules.
- UNIX-based ancillary processes.
- Dynamic graphics.

1.2.7 Subtask 8.7 - Recuperator Materials

Thin foil creep testing continued throughout the quarter. All test results to date (including prior quarters) are listed in Table 4. Results of additional creep testing performed by subcontractor Westmoreland Mechanical Testing and Research, Inc., are listed in Table 5.

The dual alloy portion of the project was begun this quarter by initiating a contract with subcontractor Belt Technologies for laser welding of the thin foils of different alloys. Evaluation of formability and other characteristics of these joints will follow.

1.2.8 Subtask 8.8 - Low Cost Combustor Materials (Ceramics)

During this quarter subcontractor LoTec furnished flexure bars, erosion plates and coefficient of expansion bars. Procurement of additional material specimens from subcontractors AEA Technologies and International Thermoproducts is also under way. During this process the requirements for test equipment are being defined by Solar.

1.2.9 Subtask 8.9 Advanced Ceramic Material

The candidate ATS component for demonstration of fabricability in a ceramic composite has been identified as the combustor to stage one nozzle transition duct. The earliest candidate was a reverse flow combustor exit duct which has since been eliminated from the ATS design. An interim candidate was an interturbine duct consisting of concentric walls connected by radial struts. The combustor duct was selected on the basis that successful execution in ceramics would conserve more cooling air than would a ceramic turbine duct. Material for the combustor duct will be B.F.Goodrich Supertemp's SiC/SiC CFCC. Solar engineers have met with the subcontractor to review the preliminary design of the duct and to determine the level of effort for the finite element analysis and life prediction testing. Total cost for this subtask will not change as a result of these negotiations.

2.0 PROGRAM SCHEDULE AND BUDGET

2.1 SCHEDULE

As of April 30, 1995, Solar's Phase II program is less than one month behind schedule. There are no visible impediments to completion of the entire Phase II scope of work by May 30, 1996, the close of the period of performance set by Revision M004.

2.2 BUDGET

As of April 30, 1995, 21,206 labor hours have been charged to the contract versus 22,448 planned. As of the same date, total program cost (including Solar's cost share) was \$2570K versus \$3155K planned. In addition to the effect of a labor underrun, further temporary cost underrun represents a billing lag wherein accumulated subcontractor costs have not yet been billed to Solar or passed through to DOE. Solar's Phase II contract is expected to finish very close to the current Labor and Cost Plans (Revision M004).

Table 4. Thin Foil Creep Test Results

Test No.	Direction	Material	t (In)	Stress (psi)	Temp(F)	5%Creep Calcul. HRS	5%Creep Actual HRS	Rupture Actual HRS
#3	Unkwn	SS 347	0.0032	17000	1300	127	166	195
#4	Long	SS 347	0.0032	17000	1300	127	165	194
#6	Long	SS 347	0.0032	17000	1200	2715	k	1500
#7	Trans	SS 347	0.0032	17000	1300	127	224	251
#8	Unkwn	SS 347	0.0032	17000	1200	2715	2391	2630
#9	Trans	SS 347	0.0032	17000	1200	2715	f	1203
#12	Long	SS 347	0.0032	17000	1250	560	l	842
#13	Trans	SS 347	0.0032	17000	1250	560	j	842
#14	Long	SS 347	0.0032	17000	1250	560	l	460
#16	Trans	SS 347	0.0032	14000	1300	277	h	220
#17	Long	SS 347	0.003	17000	1250	560	a	725
#18	Trans	SS 347	0.003	17000	1250	560	960	1025
#19	Unkwn	SS 347	0.003	14000	1300	277	b	490
#20	Trans	SS 347	0.003	14000	1300	277	700	1020
#21	Unkwn	SS 347	0.0025	11000	1300	649	1331	2080
#22	Unkwn	SS 347	0.0025	11000	1300	649	e	3773
#23	Unkwn	SS 347	0.0025	9000	1300	1170	2556	4400g
#24	Unkwn	SS 347	0.0032	12000	1250	2154	2687	3158
#25	Trans	Inconel 625	0.0037	30000	1330	1344c	109	436
#26	Long	Inconel 625	0.003	11000	1440	3360c	739	d
#27	Trans	Inconel 625	0.003	11000	1440	3360c	637	1077g

Table 4. Thin Foil Creep Test Results (Continued)

Test No.	Direction	Material	t (in)	Stress (psi)	Temp(F)	5%Creep Calcul. HRS	5%Creep Actual HRS	Rupture Actual HRS
#28	Trans	Inconel 625	0.003	8000	1480	4569c	442	696g
#29	Long	Inconel 625	0.003	8000	1480	4569c	409	685g
#30	TBD	SS 347	0.0035	7000	1350	2065	907	1527g
#31	Long	Inconel 625	0.0035	20000	1350	700	3580	n
#32	Trans	Inconel 625	0.0035	20000	1350	700	3507	n
#33	Long	Inconel 625	0.0035	30000	1330	1344c	352	750m
#34	Unkwn	Inconel 625	0.0035	15000	1350	2663	n	
#35	Unkwn	Inconel 625	0.0035	30000	1250	1099	n	
#36 340-L	Long	Inconel 625	0.0035	30000	1330	---	274	670m
#37 357-T	Trans	Inconel 625	0.0035	30000	1275	---	655q	q
#38 355-T	Trans	Inconel 625	0.0035	30000	1350	---	109	p
#39 334-L	Long	Inconel 625	0.0035	25000	1350	---	202	p
#40 353-T	Trans	Inconel 625	0.0035	22000	1480	---	7.8	23.1

a-Ruptured at 2.5% creep.
 b-Ruptured at 3.5% creep.
 c-The data is for 0.008 inch foil.
 d-Test stopped at 18% creep.
 e-Ruptured at 4.4% creep.
 f-Ruptured at 0.8% creep.
 g-Test stopped at 10% creep.
 h-Ruptured at 3.1% creep.
 i-Ruptured at 3.8% creep.
 j-Ruptured at 2.5% creep.
 k-Ruptured at 1.55% creep.
 l-Ruptured at 0.87% creep.
 m- Test stopped at 9.5% creep
 n - Test still running
 p - Test stopped at 5% creep
 q - Test stopped at 1% creep

Table 5. Thin Foil Creep Testing Summary

Specimen Number	Material	Test Stress (Ksi)	Test Temp. (°F)	5% Creep (hours)	Rupture Time (hours)
1-347	Type 347 SS	17	1225	670 ^(a)	^(a)
2-347	"	12	1300	670 ^(a)	^(a)
340-L	Inconel 625	30	1300	275	670 ^(c)
357-T	"	30	1275	670 ^(a)	^(a)
355-T	"	30	1350	109.5	^(a)
334-L	"	25	1350	201.2	^(a)
353-T	"	22	1480	6.6	23.1
394-T	N-155	18	1350	1150.0 ^(b)	^(b)
251-L	Hast-X	25	1350	32.6	^(a)
171-L	RA-85H	15	1350	3.2	3.3
317-T	Incoloy 600	17	1350	2.9	^(a)
214-L	Incoloy 825	17	1350	86.1	^(a)
113-T	Incoloy 800 H	17	1350	3.1	^(a)
14-L	Haynes 230	30	1350	40.9	^(a)
52-L	RA 333	20	1350	87.7	^(a)
154-T	HR 120	22	1350	1.23	^(a)
-----	153 MA	to be determined after elevated temp. tensile tests			

^(a) test stopped, total creep .710%

^(a) test stopped, total creep 1.28%

^(c) test stopped, total creep 9.3%

^(a) test stopped, total creep 1.03%

^(a) test stopped, total creep 5.0%

^(b) test stopped, total creep 2.50%

In addition to the charges to the contract, an additional 9249 labor hours have been charged to an internally funded project directly related to ATS. This represents cost sharing of approximately \$833,000 in addition to that provided for in the contract.

3.0 FUTURE INVESTIGATIONS

During the next quarter work on all contracted Task 8 projects will continue as planned. The topical report for the now completed Subtask 8.1 will be submitted. Subtask 8.3 - Autothermal Fuel Reformer will be completed and a topical report prepared. Subtask 8.2 - Subscale Catalytic Combustor Rig will complete its input to the design of the Full-Scale Rig (Subtask 8.7) and work will transition over to that subtask. Economic evaluation of the coal conversion defined in Task 4 will be under way.

APPENDIX 1

GLOSSARY

ACE	<u>Advanced Component Efficiency</u> . A Solar-funded multi-disciplinary, advanced technology program. It currently includes programs on compressors, turbines, cooling, and ducting.
ATS	<u>Advanced Turbine System</u> . A gas turbine-based energy conversion system as defined To the U. S. Congress by the U. S. Department of Energy (DOE). An ATS is distinguished from current gas turbines by markedly increased thermal efficiency, reliability, availability and maintainability and by decreased exhaust emissions and cost of power produced.
ATS50	Solar's designation for an ATS designed to meet the contract goal of 50 percent thermal efficiency.
ATS60	Solar's designation for an ATS designed to meet a "stretch" goal of 60 percent thermal efficiency.
BASELOAD	Typically describes a specific number of operating hours the power generation system is operating. In this case it represents (on average) 6500 hours.
BZP	<u>Barium Zirconium Phosphate</u> . A family of materials whose composition can be tailored to result in low, or zero, coefficient of thermal expansion. It is resistant to thermal shock, and is stable to 1200°C.
CFATS	<u>Coal-Fired Advanced Turbine System</u> . An advanced turbine system modified to operate on coal or coal derived fuel.
CFCC	<u>Continuous Fiber-Reinforced Ceramic Composite</u> . A high temperature composite material which consists of a ceramic matrix reinforced with fabric, tape, or rows of a high modulus fiber. CFCC's are typically not as flaw sensitive as monolithic ceramics, and can be fabricated into large parts such as combustion chambers.
CHORD	The axial length of an airfoil measured along a line drawn tangent to the leading- and trailing-edge radii. Chord is the characteristic dimension used in scaling of airfoils.
CSGT	<u>Ceramic Stationary Gas Turbine</u> . A DOE-funded program contracted to Solar Turbines Incorporated. The program goal is to demonstrate improved performance of a production gas turbine by retrofitting key components with ceramic counterparts for a 4000-hour field test.
EDX	<u>Electron Diffraction Xray</u> .

EFFECTIVENESS	(e_r for recuperator, e_i for intercooler). A characteristic of a heat exchanger -- the ratio of the amount of heat transferred to the total heat available in the hot fluid between its entry temperature and the entry temperature of the cold fluid.
EFFICIENCY, COMPRESSOR	(η_c). Ratio of the work imparted to the air flow to the total work input. Unless otherwise specified, "adiabatic" efficiency (subscript - ad) is implied, i.e., flow conditions at both inlet and outlet are in terms of absolute, or total, pressure and temperature. "Polytropic" efficiency (subscript - p) is the theoretical efficiency of a very large number of identical low pressure-ratio stages and essentially normalizes pressure ratio for comparison of differing compressors.
EFFICIENCY, THERMAL	(η_{th}). Also termed cycle efficiency. The ratio of energy input to energy output from a gas turbine. Unless specifically designated otherwise, thermal efficiency of an ATS will be defined on the basis of net power output from the turbine shaft.
EFFICIENCY, TURBINE	(η_t). Ratio of the work produced by a turbine to the work it extracts from the gas flow. When applied to a GP turbine, total-to-total efficiency is implied, this definition being based on total or absolute inlet and exit conditions. When applied to a power turbine, total-to-static efficiency is implied, thus accounting for static pressure recovery as a result of kinetic energy conversion in the exhaust diffuser.
FGM	<u>Functionally Graded Material</u> . A multi-layer material or coating system with each layer graded to provide different properties at the surface of the component relative to the core or substrate. An illustrative example would be a turbine tip-shroud with a top coating tailored for abrasability, an intermediate layer designed for oxidation resistance, and a substrate tailored for high strength.
GAS PRODUCER	(Abbr. GP) An element, or module, of a gas turbine which is required to provide a hot gas stream capable of propelling a power output turbine or other energy conversion device. As a minimum it consists of a compressor, a combustor, a turbine and associated shafting. Each of these components, in turn, may be of any of several types and may consist of one or more stages.
GPT	<u>Gas Producer Turbine</u> . May include HP and LP turbines.
GFATS	<u>Gas-Fired Advanced Turbine System</u> . An advanced turbine system which uses natural gas for fuel.
GP	See GAS PRODUCER.
HCF	<u>High Cycle Fatigue</u> . High cycle fatigue is characterized as the fatigue mechanism where vibratory loads are superimposed onto a steady state loading condition. The typical example is turbine blade under aero excitation. The turbine blade exhibits a significant steady state stress level due to the centrifugal load, where vibratory stresses are induced by high frequency pressure perturbations in the gas stream. Vibratory stress levels are typically

within the elastic range of the materials. Failures typically occur due to excitation at the component's natural frequency, setting up a resonant condition. This failure mode is associated with large numbers (10^5 - 10^7) of low stress amplitude cycles.

HIP	<u>Hot Isostatic Pressing</u> . A process for simultaneously heating a component, or powder metallurgy compact while subjecting it to isostatic pressure using an inert gas atmosphere. The temperature and pressure area are high enough to produce densification of the materials.
HP	<u>High Pressure</u> . This prefix is used to designate an individual section of a series pair of aerodynamic components operating in the high pressure regime of the two. HPC designates the high pressure compressor and HPT designates the high pressure turbine of an HP, or high pressure, spool.
INTERCOOLER	A heat exchanger placed between stages of compression in a gas turbine in order to remove heat from the compression air thereby reducing the temperature of air going to and through the succeeding stage(s).
I.O.U.	<u>Investor Owned Utility</u> . There are approximately 260 investor owned utilities in the United States. They are differentiated by the fact that they are owned through a stock ownership plan and are usually traded on the open market. they are more tightly regulated in their service area by regulatory bodies like public utility commissions than the Municipal utilities or the cooperative utilities.
IPP	<u>Independent Power Producer</u> . A non-regulated producer of electric energy. Currently the majority of these IPPs are larger power generation stations much like the Central Power Station that is owned by the Investor Owned Utilities.
LAC	<u>Levelized Annual Cost</u> . The name of the financial model used by the utilities to determine the cost of the capital equipment of the usable life of the equipment. Takes into consideration present worth arithmetic. Sometimes interchanged with book value analysis/life cycle analysis.
LCF	<u>Low Cycle Fatigue</u> . The fatigue mechanism typically associated with large thermal or mechanical loading. The cycles are typically a transient loading condition, such as start-up and shut-down of an engine. Low cycle fatigue is characterized by allowable pseudo elastic strain range for a material whereby a fatigue crack will develop after a specified number of cycles. typically LCF is considered cyclic loading of the base load leading to plastic deformation. Cycles are on the order of less than 10,000 to 15,000 cycles.
LP	<u>Low Pressure</u> . This prefix is used to designate the individual of a series pair of aerodynamic components operating in the lower pressure regime of the two. LPC designates the low pressure compressor and LPT designates the low pressure turbine of an LP, or low pressure, spool.

McrAlY A designation for an overlay coating applied to superalloy turbine components for increased oxidation and corrosion resistance. "McrAlY" is derived from the elemental constituents of the coating i.e., Cr = Chromium, Al = Aluminum, Y = Yttrium M = Ni Fe or Co (depending on substrate).

NEPA National Environmental Policy Act.

NTU Number of Transfer Units, a non-dimensional measure of the "heat transfer size" of a heat exchanger. It is defined as:

$$NTU = (A) * (U_{av})/C_{min},$$

where:

A is the heat transfer area (sqft)

U_{av} is the thermal conductance of the heat exchanger material (Btu/sec-°F /sqft)

C_{min} is the capacity rate (mCp for the fluid having the smallest capacity rate (Btu/(sec-°F)

PATTERN FACTOR (Abbr. PF). A parameter defining the range of temperatures extant in the exit gas flow from a gas turbine combustor.

$$PF = \frac{T_{MAX EX} - T_{AVG EX}}{T_{AVG EX} - T_{AVG INLET}}$$

All temperatures are absolute.

PF See PATTERN FACTOR.

PITCH The circumferential distance between two adjacent airfoils in an axial turbomachinery annulus. It is equal to 2 times pi times the radius from the annulus centerline to the subject airfoil divided by the number of airfoils in the annulus.

POWER TURBINE (Abbr. PT). A turbine stage in a gas turbine whose work output is used solely to drive the load with none being used by the compressor. In a 2-shaft gas turbine, the power turbine is fixed to a separate shaft from that of the GP turbine. It is normally -- but not required to be -- the last, or lowest pressure, turbine stage.

PR Pressure Ratio. For a compressor or compressor stage, the ratio of outlet to inlet total pressure. For a turbine or turbine stage, the ratio of inlet to outlet total pressure.

PRIS Particle Rejection Impact Separator. A device located between the primary and secondary zones of a rich-lean coal fired combustor which removes particulates from the gas stream.

PROFILE	The distribution of gas temperature within a single radial plane of a gas turbine combustor exit or other downstream annulus. The temperature profile represents the environment experienced by a turbine blade as it rotates through a temperature <u>pattern</u> thus averaging out circumferential variations. A "Profile Factor" can be defined using the Pattern Factor equation but confining the temperature data to a single radial plane.
PSR	Primary Surface Recuperator. Solar's proprietary design in which all heat exchange surfaces are "primary," i.e., transferring heat in their transverse direction. (A "secondary" surface, such as a fin, transfers heat in a lateral direction).
PT	See POWER TURBINE.
RECUPERATOR	A heat exchanger placed in the exhaust gas stream of a gas turbine in order to extract heat from the exhaust gases and return it to the cycle by heating the combustor inlet air. The term "recuperator" designates a static device as opposed to a "regenerator" which is a periodic device.
SHROUDED	A type of turbine blade design. A "shrouded" turbine features a short circumferential shroud segment attached to each blade tip. Together, these segments make up a full circular, rotating shroud. The outside surface of this shroud normally carries one or more circumferential seal elements. Conversely, a "non-shrouded" turbine is characterized by open blade tips rotating in close proximity to a stationary shroud.
SPOOL	The compression and expansion element of a gas producer, consisting of a compressor, a turbine and associated shafting. The turbine is designed so as to provide the amount of work required for the compression process plus any mechanical losses. A gas producer includes one or more spools and will be designated as 1-spool, 2-spool, etc.
SR	<u>Stress Rupture</u> . Stress rupture is the failure mechanism where gross rupture occurs due to time dependent deformation caused by steady stress at elevated temperatures. The mechanism at intermediate stages of deformation is called creep and is measured in terms of plastic strain. Stress rupture is usually associated with the Larson-Miller Parameter (LMP) which correlates the relationship between service life in hours and service temperature at a constant stress level. For a given material, Larson-Miller Parameter curves are developed which depict the LMP as a function of steady stress level.
STAGE WORK FACTOR	The ratio of work actually performed by a flow of cooling air within a turbine stage, to that possible if the flow were added to the hot gas stream.
STALL	A condition arising in one or more stages of an axial compressor in which the design pressure-velocity-rotational speed relationship is disrupted such that separation of the air flow from the blade contour occurs.
STANDBY	Use as a descriptor of a power generation station or unit that is only drawn upon when there is a demand. It currently is thought of as an emergency

back-up unit in case the primary system fails, or when the primary unit cannot meet the load demand. Sometimes called an "on-demand" system.

SURGE	The condition occurring when a compressor is operated below its minimum stable air flow rate for a given rotational speed. Surge is characterized by cyclic backflow of air in the flowpath accompanied by violent pressure fluctuations. During surge all stages of the compressor will be in a stall condition.
TBC	<u>Thermal Barrier Coating</u> . A thermally insulating ceramic coating (ZrO_2) applied to superalloy combustor and airfoil components. The insulative properties of the coating allow increased turbine inlet temperatures while maintaining acceptable metal substrate temperatures.
T&D	<u>Transmission and Distribution</u> . The system used to get the power (or fuel) from the point of origin to the consumer.
TRIT	<u>Turbine Rotor Inlet Temperature</u> . The average gas temperature entering the rotor annulus of the first turbine stage in a gas turbine. It is less than the average combustor exit temperature due to the mixing of spent cooling air flow from upstream sources, primarily the first stage nozzle vanes.
TSSC	<u>Two-Stage Slagging Combustor</u> .
ZWEIFEL COEFFICIENT	A measure of turbine blade loading based on pitch/chord ratio and gas turning angle as independent variables.