Advanced Turbine Systems Program - Conceptual Design and Product Development

**Quarterly Report
August 1 - October 31, 1995**

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EXECUTIVE SUMMARY

This Quarterly Technical Progress Report covers the period, August 1, 1995 through October 31, 1995, for Phase II of the Advanced Turbine Systems (ATS) Program by Solar Turbines Incorporated under DOE contract No. DE-AC21-83MC30246. 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. Final editions of these topical reports have been submitted to the DOE. This quarterly report, then, addresses only Task 4 which was completed during the quarter 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

Two of these nine subtasks (8.1 and 8.3) were completed during the quarter and Topical reports submitted to the DOE.

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

- In Subtask 8.2 - Sub-scale Catalytic Combustion Rig - peak to peak variations in fuel air mixture delivered to the catalyst face were demonstrated at 5 percent and below. This confirms the possibility of operating a full-scale catalytic combustor below the target of 5 ppmv of NOx.
- In Subtask 8.4 - Dual-Alloy Turbine Disc - successful hot isostatic press (HIP) solid state bonding of the Mar-M-247 rim alloy to the Udimet 720 hub alloy was demonstrated. Two competing methods which produced unsuccessful results at higher cost were dropped from the program and HIP-bonding development will now proceed to larger scale demonstrations.
- In Subtask 8.7 - High Temperature Recuperator - successful laser welding and electron beam welding of Inconel 625 alloy (high temperature) to Type 347 stainless steel (moderate temperature) foil has been demonstrated. The welded foils were then successfully folded into primary surface recuperator finned sheet stock.

Solar attended the annual ATS Program Review at METC on October 16-18. Presentations regarding the overall ATS program were made by Dave Esbeck, Vice President of Engineering, by Steve Gates, ATS Director. ATS-related presentation were made by Mark Van Rode (Ceramic Retrofit Program), Tom Duffy (High Pressure Steam Turbine and Dave White (Gas Turbine/Fuel Cell integration).

Approximate* contract labor and cost status as of October 31, 1995:

Labor: 27,700 hours versus 27,626 planned.

Total Program Cost**: \$3751K versus \$4093K planned.

*Cost and Labor Status Reports submitted to DOE as of October 31, 1995, contain an internal accounting error to be corrected in the November status reports.

**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, 4, 5, 6 and 7 have been completed and topical reports submitted for each.

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). This task was completed during this quarter and a topical report submitted to the DOE.

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

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

It was concluded in Task 4 that, for Solar's recuperated ATS engine, gasification of the coal was the most feasible with indirect firing as the second choice. Gasification allows retention of most of the hardware from the GFATS configuration and minimizes the amount of modification required by the combustor and control system. The possibility of plugging of the recuperator with particulate matter eliminates direct firing and PFBC from consideration.

1.2 TASK 8 - DESIGN AND TEST OF CRITICAL COMPONENTS

During this quarter, work progressed on eight of nine subtasks in Task 8. One, Task 8.1 - Low Pressure Drop Recuperator - was completed in the prior quarter and a topical report submitted. A second completion, Task 8.3 - Autothermal Fuel Reformer - occurred in this quarter with submission of a topical report.

1.2.1 Subtask 8.2 - Subscale Catalytic Combustion Rig

This subtask was formerly titled, "Low Pattern Factor Combustor" as part of the original content of Task 8. Together with Subtask 8.5 added by Revision A003 to the contract, it becomes a part of an overall catalytic combustion project.

Fuel-air premixing measurements were performed under test conditions using a "dummy" (chemically non-reactive) catalyst bed instrumented with 30 sampling probes. The purpose of this test is to compare results with premixing measurements made at atmospheric pressure. There was poor correlation between the two tests, which could explain the local overheating observed during the previous test (reported in the July monthly report) in spite of the good fuel-air profiles obtained in the atmospheric test.

Alternate fuel injection schemes which can be scaled up to full scale conditions are being investigated. Catalyst bed evaluation will proceed once adequate premixing is achieved at operating pressure.

Based on previous fuel-air premixing measurements, the next method selected for improvement of the initial fuel dispersion was to increase the number of fuel injection locations. This modification was incorporated in a new premixer.

An alternate premixer design was also investigated. This design relies on a single rapidly converging bend to drive the fuel-air mixing. The device consists of an annular flow section where the air enters radially at the rear of the premixer and the fuel is injected at multiple points. The air and fuel then enter a 180-degree bend where the drastic contraction of flow is expected to induce mixing.

These two premixers were evaluated on the atmospheric pressure premixing rig. Satisfactory fuel-air mixing was obtained with both premixers - 3 percent peak-to-peak variation with the first and 7 percent with the second premixer.

Mixing measurements were conducted with the first premixer - incorporating the static mixers - under simulated ATS full-load operating conditions. Peak-to-peak variations less than 5 percent were demonstrated.

1.2.2 Subtask 8.3 - Autothermal Fuel Reactor (ATR)

Autothermal fuel reforming (ATR) consists of reacting a hydrocarbon fuel such as natural gas or diesel with steam to produce a hydrogen-rich "reformed" fuel. The ATR task work has been designed to investigate the fuel reformation and the product gas combustion under gas turbine conditions. The hydrogen-rich gas has a high flammability with a wide range of combustion stability. Being lighter and more reactive than methane, the hydrogen-rich gas mixes readily with air and can be burned at low fuel/air ratios producing inherently low emissions. The hydrogen-rich reformed fuel also has a low ignition temperature which makes low temperature catalytic combustion possible - another factor contributing to low NO_x emissions. ATR can be designed for use with a variety of alternative fuels including heavy crudes, biomass and coal-derived fuels. When the steam required for fuel reforming is raised by using energy from the gas turbine exhaust, cycle efficiency is improved because of the steam and fuel chemically recuperating.

The basic ATR research conducted in this subtask showed that 65 to 75 percent hydrogen can be produced in a secondary fuel resulting from the reformation of both natural gas and liquid (diesel No. 2) fuels. These results were demonstrated first in a batch tube reactor and later in a complete ATR rig. The work covered a range of reforming temperatures 1300°F to 1600°F under operating pressures from 60 to 120 psig. Steam-fuel ratios ranging from 0.3:1 to 1.0:1 were used in the investigation.

In addition, autothermal fuel reformation system durability tests were conducted to investigate the catalyst life and the effect of acidic compounds (e.g., H₂S, HCl) found in raw natural gas on the

reforming performance. An absorbent consisting of zinc and calcium dual-oxides was selected for removing these acidic species and served as a polishing step to ensure a consistent fuel quality. The durability tests with an absorber bed resulted in obtaining high hydrogen (65 to 75 percent on a dry basis) product gases under the steady-state operation. No catalyst deactivity was found after the extended testing when using a fuel mixed with hydrogen sulfide (H_2S) at a concentration of 200 times higher than that in the local natural gas. Analyses of the used catalyst by electronic diffraction X-ray showed no accumulation of sulfur on the catalyst. The results also indicated that the catalyst activity can be regenerated by steaming the used catalyst after duration testing.

Results of the test work suggest that fuel reformation is a promising approach to the clean combustion for gaseous and liquid fuels. The unusual fuels that normally present problems with meeting clean air requirements could be handled via fuel reforming to generate hydrogen-rich gases prior to combustion. Fuel reformation would allow a single fuel injector and combustion system to be employed in a gas turbine regardless of the parent fuel to meet customer specified requirements. A fully developed autothermal reformer would bring fundamental benefits to the advanced turbine system (ATS) on reducing emissions, increasing thermal efficiencies and improving fuel flexibility.

This completes work on the autothermal fuel reformer under Solar's ATS Phase II contract. The (draft) Topical Report was submitted to DOE on October 11, 1995. Continuing work on fuel reformation will be conducted as a part of Solar's internal R&D program.

1.2.3 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.

Early in the quarter some final characterizations of the machined joint surfaces were completed prior to committing the material to bonding trials. The surfaces were examined in the Scanning Electron Microscope in order to detect any potential contamination that may have transferred from the tool bits during machining. The analysis showed that no carbide cutting tool residue was left on the bond surface.

The final selection of boron level for the boronize-bonding process was completed. Five boron levels ranging from 0.0031 gm/sq-in to 0.0086 gm/sq-in were evaluated. Metallographic examination and electron microprobe analysis showed that 0.005 gm/sq-in provided the best balance of bonding with minimum porosity and avoiding unwanted boride phase formation after HIP bonding. Based on this result, the subscale disks are being boronized by Materials Development Corporation at the 0.005 gm/sq-in level.

Preliminary examinations of the solid-to-solid HIP-bonded and boronize HIP-bonding discs were positive. The assemblies were HIPed at 2050°F and 15ksi. Thus far the examinations have been macroscopic on rough polished full sections. Detailed examination of metallographic mounted specimens will be performed to judge the quality of the bond joint after heat treatment. If the bonds appear acceptable, the specimens will progress into mechanical property testing.

The first shear-forge bonding effort at Ladish Company was also completed. Results on two subscale assemblies have indicated that the initial shear-forge temperature of 2050°F is not high enough for this material combination. It appears that the CM 247 LC cast rim material was too hard

at this relatively low forge temperature. This results in rounding/dulling of the molybdenum shear tool and incomplete bonding of the two materials. Ladish has recommended that the shear-forge temperature be increased to 2175°F in order to solve the problem. It was originally hoped to maintain all bonding temperatures below the gamma-prime solvus (grain-coarsening) temperature of 2050°F for Udimet 720. However, to demonstrate the shear-forge process it is clear that the temperature must be increased. The impact of the higher temperature will be a slight reduction yield strength and low cycle fatigue capabilities of the Udimet 720.

A critical milestone in the program has been reached in that the solid-to-solid hot isostatic pressing (HIP) process has thus far produced very high quality bonds and has therefore been down-selected for the remainder of the development program. Solid-to-solid HIPing is also projected to be the lowest cost of the three bonding techniques investigated. As described above, the shear-forge method (Ladish Co.) did not produce complete fusion between the CM 247 and Udimet 720 alloys when bonded at 2050°F. Subsequent trials at 2175°F did not solve the problem. Based on these results, shear-forge was dropped from further consideration. The remaining trial materials from the shear-forge effort have been committed to scale-up of the solid-to-solid HIP bonding process.

The two subcontracts with Southwest Research Institute (SwRI) are now in full swing. In the first effort, "Development of Life Prediction Methodologies," raw materials are being sectioned for mechanical testing and the tensile, creep and low cycle fatigue test matrix is being finalized. Solar has provided SwRI with the required design and stress analysis input required to proceed. In the second effort, "Eddy Current Inspection Techniques for Turbine Disks," the inspection equipment for the development program has been finalized and probe design is under way. Solar provided disk materials for experimentation.

Efforts in the life prediction program during this period included finalizing the mechanical test plan, fabrication of the test specimens, and initiation of all the long-term creep tests. Some of the first creep results have shown the spraycast CM 247LC material may not have sufficient rupture properties to meet the original 1400°F disk rim temperature goal. It appears the low rupture strength is the result of the very fine grain size (ASTM No. 6), which we now understand is a characteristic of the spray cast process that is difficult to modify. On the other hand, early tests at Solar have shown the fine grain material has outstanding Low Cycle Fatigue (LCF) properties at the anticipated ATS operating conditions. The potential for this trade-off between creep and LCF properties due to grain size was anticipated (although the degree was underestimated). Therefore, a coarse grain version of CM 247LC (Grainex Process) with improved creep resistance was planned in the follow-on Phase III program in this event. The Grainex material has been cast by Howmet and a parallel test program is beginning. Ultimately, having a database for the two materials will be valuable for understanding the effect of grain size on creep-fatigue life. In addition, the fine grain spraycast CM 247LC material may have applications in other types of components which are more fatigue limited.

1.2.4 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 earlier and placed on hold in order 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 continuing development of fuel injection methods for obtaining satisfactory catalyst inlet velocity and fuel/air mixture profiles and to providing sufficient post-catalyst volume to

enable more complete CO burn out. These features have now been defined and the rig is in the final fabrication stage.

1.2.5 Subtask 8.6 - Total Plant Controls

During this quarter, the man-machine Interface (MMI) ergonomics were reviewed with a human factors consultant and the Windows NT operating system was examined as an alternative to the Unix operating system. A detailed software module architecture was drafted and reviewed.

Completion of the study comparing UNIX and Windows NT as candidates for the operating system has resulted in the selection of Windows NT. This system has the advantage of ready acceptance in Solar's marketplace and better software development tools than UNIX.

A specification for a prototype was developed. The prototype will demonstrate the look and feel of the overall system as well as some of the advanced features. A project plan has been set up to guide the team in the development of this prototype. The prototype is targeted to be completed in December.

Commercial data acquisition drivers were obtained, installed and tested in the Windows NT environment. The prototype development environment has been set up.

1.2.6 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 1. Results of additional creep testing performed by subcontractor Westmoreland Mechanical Testing and Research, Inc., are listed in Table 2.

Modified stainless steel 310 material was recently manufactured by Carpenter Technologies and delivered as rough forgings to Oak Ridge National Laboratory for testing. Two versions of modified 310 were made. Both contain solid solution strengtheners for increased creep strength. One material contains some molybdenum containers whereas the other material has a tantalum container. The rolled material will be used to make samples for tensile, oxidation and creep tests.

ORNL completed hot rolling and surface grinding of the two heats of experimental modified 310 stainless steel to a thickness of 5/8 inch. The material has now been further rolled to 0.020-inch. Solar will begin initial tensile and creep testing on the sheet material, and will decide whether committing a portion to rerolling to foil (0.004-in) is appropriate. The rerolling effort is currently on hold at ORNL. Because of this, there is no new progress to report for October.

A dual alloy recuperator is a recuperator constructed of thin foil material that includes a width of one stainless material, such as SS-347, along with a narrower strip of higher temperature alloy, such as Inconel 625 or Haynes 230. A major portion of a recuperator core would experience lower temperatures and could be constructed of a less expensive alloy than if the core were made of only one material. This concept, if successful, could extend the use of stainless 347 to even higher temperature cycles. The present concept is to use approximately one-sixth of Inconel 625 and five-sixths of stainless 347. This would greatly decrease the material cost required for a higher temperature cycle.

The dual-alloy recuperator effort is progressing well, with both laser and EB welding techniques successfully applied. Belt Technologies, Inc. finished welding 12 in. x 12 in. bi-metal 347 stainless Steel/Inco 625 alloy as a scale-up demonstration.

Table 1. Thin Foil Creep Test Results.

Test No.	Direction	Material	t (in)	Stress(psi)	Temp(F)	5%Creep Calculated HRS	5%Creep Actual HRS	Rupture Actual HRS
#1	Long	SS 347	0.0032	17000	1300		discontinued	
#2	Trans	SS 347	0.0032	17000	1300		discontinued	
#3	Unknown	SS 347	0.0032	17000	1300	127	166	195
#4	Long	SS 347	0.0032	17000	1300	127	165	194
#5	Unknown	SS 347	0.0032	17000	1300		discontinued	
#6	Long	SS 347	0.0032	17000	1200	2715	k	1500
#7	Trans	SS 347	0.0032	17000	1300	127	224	251
#8	Unknown	SS 347	0.0032	17000	1200	2715	2391	2830
#9	Trans	SS 347	0.0032	17000	1200	2715	l	l
#10	Long	SS 347	0.0032	17000	1250		discontinued	
#11	Trans	SS 347	0.0032	17000	1250		1741	a
#12	Long	SS 347	0.0032	17000	1250	580	i	i
#13	Trans	SS 347	0.0032	17000	1250	580	j	j
#14	Long	SS 347	0.0032	17000	1250	580	l	l
#15	Trans	SS 347	0.0032	17000	1250		discontinued	
#16	Trans	SS 347	0.0032	14000	1300	277	h	h
#17	Long	SS 347	0.003	17000	1250	580	a	a
#18	Trans	SS 347	0.003	17000	1250	580	880	1025
#19	Unknown	SS 347	0.003	14000	1300	277	b	b
#20	Trans	SS 347	0.003	14000	1300	277	700	1020
#21	Unknown	SS 347	0.0025	11000	1300	848	1331	2080
#22	Unknown	SS 347	0.0025	11000	1300	848	e	e
#23	Unknown	SS 347	0.0025	9000	1300	1170	2556	g
#24	Unknown	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	g

Table 1. Thin Foil Creep Test Results (Continued)

Test No.	Direction	Material	t (in)	Stress (psi)	Temp (F)	8% Creep Calcul. HRS	8% Creep Actual HRS	Rupture Actual HRS
#28	Trans	Inconel 625	0.003	6000	1480	4566c	442	g
#29	Long	Inconel 625	0.003	6000	1480	4566c	409	g
#30	TBD	SS 347	0.0035	7000	1350	2085	907	g
#31	Long	Inconel 625	0.0035	20000	1350	700	3590	n
#32	Trans	Inconel 625	0.0035	20000	1350	700	3507	n
#33	Long	Inconel 625	0.0035	30000	1330	1344c	352	m
#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	m
#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
41	Long	Haynes 230	0.003	20000	1300	—	n	
42	Trans	Haynes 230	0.003	20000	1300	—	n	

a-Test stopped at 2.5% creep
 b-Test stopped at 3.5% creep
 c-The data is for 0.006 inch foil
 d-Test stopped at 18% creep
 e-Test stopped at 4.4% creep
 f-Test stopped at 0.6% creep
 g-Test stopped at 10% creep
 h-Test stopped at 3.1% creep

i-Test stopped at 3.8% creep
 j-Test stopped at 2.5% creep
 k-Test stopped at 1.55% creep
 l-Test stopped 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 2. 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%

^(b) test stopped, total creep 1.28%

^(c) test stopped, total creep 9.3%

^(d) test stopped, total creep 1.03%

^(e) test stopped, total creep 5.0%

^(f) test stopped, total creep 2.50%

These welded prototype 12 in. x 12 in. samples were received by Solar for evaluation. A portion of the material was submitted to Morton Metalcraft for folding trials. Both electron beam and laser welded samples were successfully folded in these trials. The remainder is being sectioned for tensile and creep testing to be performed at Westmoreland Mechanical Testing and Research, Inc., in Youngstown, Pennsylvania. Crushing tests will also be done to see how well the material performs. Folding and crushing are two critical foil manufacturing operations.

1.2.7 Subtask 8.8 - Low Cost Combustor Materials (Ceramics)

This subtask was originally titled "Reheat Combustor Material" and was proposed in anticipation of future addition of a reheat combustor to the ICR gas turbine cycle defined in Task 3. With the migration to the optimized recuperated cycle defined in Task 6, the goal of the subtask was changed to the evaluation of materials suitable for use in gas turbine combustion liners. It now supplements similar work being conducted by Solar under DOE Contract No. DE-AC02-82CE40960 titled "Ceramic Stationary Gas Turbine (CSGT) Development." The use of ceramic combustor liner in gas turbines contributes toward emissions reductions by freeing cooling air for use as primary combustion air and by allowing higher wall temperatures which contribute to the more complete combustion of hydrocarbons.

The planned approach is to obtain material properties from flexure bars and then to test each candidate material in an 8-inch diameter combustor can under actual conditions of gas turbine combustion.

Initially, three candidate materials were selected for evaluation. These are listed in Table 3. AEA Technologies, a U.K. firm, became unable to participate under the intended schedule due to organizational and other changes relating to their recent privatization. The material selected to replace the AEA material is Nextel 550, a reinforced silica-alumina composite from Scientific Applications International Corp. (SAIC). Testing of all three materials will begin during the next quarter.

Table 3. Candidate Ceramic Materials for the Reheat Combustor Application

Material Name	Type	Supplier
B-30	BZP	LoTEC
Altra KVS 16	high alumina fiber reinforced composite	International Thermoproducts
System 2.2 High Temperature Composite	Glass-Ceramic Fiber reinforced composite	AEA Technology

1.2.8 Subtask 8.9 - Advanced Ceramic Material

The goal of this subtask is to explore the use of advanced ceramic composite materials in gas turbine components. This will include development of a suitable (cost-effective) component fabrication process, the development of a finite element stress analysis to assure 30,000 hours of component life and the actual fabrication of a demonstration article.

The majority of the task has been subcontracted to the Supertemp Division of B.F. Goodrich Aerospace. Materials considered are both carbon-reinforced silicon carbide (SiC) or silicon carbide-reinforced silicon carbide (SiC/SiC).

A combustor to nozzle transition duct will be fabricated by subcontractor B.F. Goodrich Supertemp (BFG) in this task. A Pro-E computer model of the duct has been completed by Solar and is ready for review by BFG. Solar and BFG will then iterate on the design to arrive at final dimensions for fabrication.

2.0 PROGRAM SCHEDULE AND BUDGET

2.1 SCHEDULE

As of October 31, 1995, Solar's Phase II program is approximately on 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 October 31, 1995, 27,700* labor hours have been charged to the contract versus 27,626 planned. As of the same date, total program cost (including Solar's cost share) stand at \$3751K* versus \$4093K planned. This 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).

- * These figures are "approximate" in that they were obtained by manual subtraction of an erroneous charge made to the contract during October. This erroneous charge will be removed via a credit entry to the November Labor and Cost Status Reports.

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

Seven months remain in Solar's ATS Phase II contract. During this period the remaining seven subtasks in Task 8 will be completed and a topical report submitted for each. Work on the contract will be completed with the preparation and submission of a Final Technical Report.

On September 14, Solar was awarded Cooperative Agreement # DE-FC21-95MC-31173 by the DOE for performance of Phases III & IV of the ATS program. The Statement of Work (SOW) for this agreement includes continuation of certain technology projects contained in Phase II, Task 8. Specifically, these include Catalytic Combustion (Subtasks 8.2 and 8.5), Dual-Alloy Turbine Discs (Subtask 8.4), Ceramics (Subtasks 8.8 and 8.9) and Recuperator Materials (Subtask 8.7). Solar's ATS Phase III Technology Team Leaders are preparing detailed milestone plans for these projects which will include an orderly transition from Phase II advance efforts.

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	(ϵ_r for recuperator, ϵ_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	Functionally Graded Material. 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	Gas Producer Turbine. May include HP and LP turbines.
GFATS	Gas-Fired Advanced Turbine System. An advanced turbine system which uses natural gas for fuel.
GP	See GAS PRODUCER.
HCF	High Cycle Fatigue. 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 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.
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 pattern 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	Stress Rupture. 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	Thermal Barrier Coating. 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	Transmission and Distribution. The system used to get the power (or fuel) from the point of origin to the consumer.
TRIT	Turbine Rotor Inlet Temperature. 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	Two-Stage Staging Combustor.
ZWEIFEL COEFFICIENT	A measure of turbine blade loading based on pitch/chord ratio and gas turning angle as independent variables.