**Advanced Turbine Systems Program
Conceptual Design and Product Development**

**Annual Report
August 1994 - July 1995**

November 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

MASTER

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Office of Fossil Energy
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P.O. Box 880
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CONTENTS

<u>Section</u>		<u>Page</u>
	EXECUTIVE SUMMARY	1
1	TASK 1 - PROJECT PLAN	3
2	TASK 2 - INFORMATION REQUIRED FOR NATIONAL ENVIRONMENTAL POLICY ACT (NEPA)	5
3	TASK 3 - SELECTION OF GFATS CYCLE	6
4	TASK 4 - CONVERSION TO A COAL-FUELED ADVANCED TURBINE SYSTEM (CFATS)	8
5	TASK 5 - MARKET STUDY	9
	5.1 Approach	9
	5.2 ATS Market Application	9
	5.2.1 Electrical Power Generation	9
	5.2.2 Oil and Natural Gas Production, Transmission and Storage	11
	5.2.3 Industrial Prime Movers	11
	5.2.4 Marine Propulsion	12
	5.3 Market Requirements	12
	5.4 Competing Technologies	12
	5.5 Method and Results	12
6	TASK 6 - SYSTEM DEFINITION AND ANALYSIS	14
	6.1 System Selection	14
	6.2 Conceptual Design	15
	6.3 Recuperated Gas Turbine Cycle Characteristics	16
	6.4 ATS Compressor	17
	6.5 ATS Recuperator	18
	6.6 ATS Combustor	19
	6.7 ATS Gas Producer Turbine	23
	6.8 ATS Power Turbine	24
	6.9 ATS Control System	26
	6.10 ATS Overall System Design	26
7	TASK 7 - INTEGRATED PROGRAM PLAN	29
8	TASK 8 - DESIGN AND TEST OF CRITICAL COMPONENTS	32
	8.1 Low Pressure Drop Recuperator (Subtask 8.1)	32
	8.2 Sub-Scale Catalytic Combustor Rig (Subtask 8.2)	33

CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
	8.3 Autothermal Fuel Reformer (Subtask 8.3)	37
	8.4 Dual Property Turbine Disc (Subtask 8.4)	40
	8.5 Full-Scale Catalytic Combustor Rig (Subtask 8.5)	41
	8.6 Total Plant Controls (MMI) (Subtask 8.6)	42
	8.7 High Temperature Recuperator Materials (Subtask 8.7)	43
	8.8 Low Cost Ceramic Materials	48
	8.9 Advanced Ceramic Materials (Subtask 8.9)	49
9	SCHEDULE AND BUDGET	50
	9.1 Schedule	50
	9.2 Budget	50
	9.3 Future Investigations	50
	GLOSSARY	51

FIGURES

Figure		Page
1	ATS Program Schedule	4
2	QFD Chart	10
3	Solar's Advanced Turbine System (Cross-Section)	15
4	ATS Combustor	17
5	Primary Surface Sheets	19
6	PSR Air Cell	19
7	PSR Core Assemblies	19
8	Representative Combustor Performance Map	20
9	Engine Cross-Section Showing Can-Annular Catalytic Combustor	22
10	ATS Ultra Lean Premixed Combustor Approach	22
11	SoLoNOx Combustor Liner (left) and Fuel Injector (right)	22
12	ATS Turbine Configuration Showing 'Close-Coupled' GP to PT Transition Duct	25
13	ATS Subsystems and Features	27
14	View of Integrated Design Package	28
15	Catalyst Inlet Velocity Profiles	35
16	Subscale Catalytic Combustor Test Rig Configured to Flatten Catalyst Inlet Velocity Profile	35
17	Catalytic Combustor Results	36
18	Temperature Readouts Monitored by Thermocouples	39
19	Flattened Tubes Tests and FEM Strain Comparison at Room Temperature	48

TABLES

<u>Table</u>		<u>Page</u>
1	Pugh Chart	10
2	Competing Systems for Electrical Generation	13
3	Range of TIT, Cooling and Efficiency at Selected PR for Solar's ATS	17
4	ATS Compressor Performance	18
5	ATS Recuperator Performance	18
6	ATS Combustor Performance	21
7	Comparison of ATS Gas Producer Turbine With Baseline	23
8	Performance of ATS Gas Turbines	24
9	Comparison of ATS Power Turbine With Baseline	25
10	Recuperator Alloy Candidates	44
11	Thin Foil Creep Test Results	45
12	Thin Foil Creep Testing Summary	47
13	Candidate Ceramic Materials for the Reheat Combustor Application	49

EXECUTIVE SUMMARY

This Yearly Technical Progress Report covers the period, August 1, 1994, through July 31, 1995 for Phase II of the Advanced Turbine Systems (ATS) Program by Solar Turbines Incorporated under D.O.E. Contract No. DE-AC421-93MC30246. As allowed by the Contract (Part III, Section J, Attachment B) this report is also intended to fulfill the requirements for the fourth quarterly report for the second year of the Contract.

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 in the year 2000.

During the period covered by this report, Solar completed an additional three (for a total of six completed) of eight program tasks as well as one of nine subtasks under Task 8 - Design and Test of Critical Components. Topical Reports were submitted for each of these four completions.

Tasks completed are summarized as follows:

Task 5 - Market Study - defined the markets that can be served by Solar's ATS, outlined the product characteristics required by these markets, reviewed the competing technologies that can serve them, conducted a life-cycle cost analysis of ATS against those technologies and forecast the total size of an ATS market out to the year 2020. Major demand for ATS product was forecast to occur in two sizes, 5 and 15 MWe. A total of 26,880 megawatts of electrical generating capacity (MWe) powered by Solar's ATS gas turbines totaling 36 million horsepower is forecast to be installed by the year 2020. At this point 0.82 quadrillion Btu's of fossil energy will have been saved worldwide by a DOE/Solar introduction of the ATS. Also, in the year 2020, worldwide emission of NOx will have been reduced by 343,000 tons per year.

Task 6 - System Definition and Analysis - defined an optimized recuperated gas turbine as the prime mover meeting the requirements of the Task 5 Market Study and whose characteristics were, in turn, used for forecasting the total ATS future demand. This machine is one in which the characteristics of the cycle (pressure ratio, firing temperature, etc.) of the core engine are optimized for use with a recuperator with no regard for any possible simple-cycle (non-recuperated) applications. The resulting gas turbine will operate at a pressure ratio of approximately 9:1 and a firing temperature in the neighborhood of 2150°F (TRIT). Utilizing advanced turbine cooling technology to minimize cooling air bleed, the cycle will operate at an ISO, no-loss thermal efficiency of 43.5% at the turbine shaft. NOx emission will be held to less than 10 ppmv and CO and hydrocarbon emissions to less than 15 ppmv.

The performance of this prime mover is further enhanced by the application of new technologies in the control system and engine support systems that Solar will supply in integrating it into a packaged gas turbine system ready for installation and commissioning at a customer site.

Task 7 - Integrated Program Plan - defines a program which will develop the ATS described by Task 6 to a state of readiness for field test in the third quarter of 1998 and for commercial introduction in the first quarter of 2000. This plan is based on full utilization of Solar's internal resources as well as those of teaming partners and subcontractors. The plan provides careful management of both technical and commercial risks and will be operated within Solar's highly successful New Product Introduction (NPI) discipline. Program control

(schedule and budget) will be administered through Solar's existing, ISO 9000-certified internal systems.

Task 8.1 - Low Pressure Drop Recuperator - utilized the resources of the Caterpillar Technical Center to demonstrate that Solar's current primary surface recuperator (PSR) will provide the high thermal effectiveness and low pressure loss required to support the proposed ATS cycle defined in Task 6. A performance rig consisting of a full-scale section of the PSR was run at both design and off-design conditions. These results, together with supplemental heat transfer surface basic characteristics obtained from a transient test rig will provide the necessary data to calculate PSR performance over a wide range of ATS operating conditions. These cycle calculations will serve as predictors for performance measured on all-up engine tests during the development program.

Results from Tasks 5, 6 and 7 were used in preparing a proposal for Phases 3A, 3B and 4 of the ATS Program in response to the DOE's Solicitation for Cooperative Agreement Proposal (SCAP), DE-SC21-94MC31173, titled, "Industrial Advance Turbine Systems (ATS) Development and Demonstration." Solar's proposal was submitted on October 25, 1994, and has been supported in the interim by Solar's response to various requests for clarification, etc. by the DOE.

On September 27, 1994, the Contract was modified by revision A003 which adds six subtasks to the three original subtasks included in Task 8 - Design and Test of Critical Components. Task 8 now provides a full set of early activity in the area of combustion systems, material technology and advance engine control systems that will be required for a successful ATS. Revision M004 later extended the period of performance of the contract from November 30, 1995, to May 30, 1996, in order to allow for full completion of the added subtasks.

As of July 31, 1995, a total of 23,276 labor hours have been charged to the contract versus 25,036 planned. Total program cost (including Solar's cost share) stands at \$3016K versus \$3693K planned. The current cost underrun is temporary and results from the accumulation of cost by subcontractors and not yet billed to Solar. An additional 9249 labor hours have been charged to internally-funded development activity in direct support of ATS Phase II. This represents some \$833,000 of cost sharing by Solar in addition to that provided for in the contract.

Three briefings to DOE's COTR and other staff were held during and near the period covered by this report:

Date	Location	Subject
07/28/94	DOE-METC	System modifications indicated by the Market Study
01/18/95	Solar	Six-months' ATS Phase 2 briefing
08/15/95	DOE-METC	Six-months' ATS Phase 2 briefing

Solar prepared and presented two papers at the DOE's ATS Annual Review in November of 1994:

- "Advanced Turbine Systems Overview," by D.A.Rohy.
- "Gas Fired Advance Turbine System," by K.W.Karstensen.

SECTION 1

TASK 1 - PROJECT PLAN

Task 1 was completed and a Topical Report was submitted in December 1993. The plan submitted was structured to follow the contractual Statement of Work (SOW). This format was implemented in order to simplify the presentation of the plan and to show the interaction of the several tasks. Each of these tasks was discussed at length in terms of the work to be performed and the criteria used to define task completion. Cost and Labor Plans were submitted with Task 1 Topical Report as well as the schedule of Phase II work as shown below in Figure 1. Solar's performance to schedule and budget will be discussed in Section 9 of this report.

The Task 1 Topical report was amended by a revised Management Plan submitted March 20, 1995, covering two contract changes as follows:

Amendment A003, dated September 27, 1994, added six additional subtasks to Task 8 - Design and Test of Critical Components. This additional work was proposed by Solar in order to provide additional risk reduction by adding more early development of technologies critical to the ATS Program. These added subtasks are as follows:

<u>Subtask No.</u>	<u>Title</u>
8.4	Dual-Alloy Turbine Disc
8.5	Full-Scale Single Can Catalytic Combustor Rig
8.6	Advanced Control System (MMI)
8.7	High Temperature Recuperator Materials
8.8	Low Cost Ceramic Materials
8.9	Advanced Ceramic Materials (Composite)

Modification M004, dated March 13, 1995, extends the period of performance of the contract by six months (from November 30, 1995, to May 30, 1996). This modification changes the original schedule for the subtasks added by Amendment A004 so as to reflect a later start date. This later start date was occasioned by a delay in the funding of this additional work.

Figure 1. ATS Program Schedule

SECTION 2

TASK 2 - INFORMATION REQUIRED FOR NATIONAL ENVIRONMENTAL POLICY ACT (NEPA)

The Topical Report for Task 2 was submitted in November 1993. This Report covered the original contract scope of work. Solar submitted its proposal for add-on subtasks under Task 8 in January, 1994. Information required for NEPA pertaining to these add-on subtasks was provided to DOE by letters in January and February, 1994 as requested. DOE informed Solar in February that it was authorized to perform Task 8 work (original scope of work), pursuant to Task 2 and NEPA.

An amended Task 2 Topical Report was submitted on November 18, 1994, which covers the activities added by Amendment A003 to the contract. The addition of these activities did not change the level of compliance with NEPA.

SECTION 3

TASK 3 - SELECTION OF GFATS CYCLE

Task 3 was completed in April 1994 and the final revision to the Topical Report submitted in July. This task identified an intercooled and recuperated (ICR) gas turbine as the eventual Solar product to result from Solar's internal New Product Introduction (NPI) program combined with DOE's ATS program. When fired in the region of 2500°F at the optimized pressure ratio, this machine will be capable of operating at 50 percent thermal efficiency (turbine shaft power/fuel LHV). Task 3 activity was centered around determining the sensitivity of cycle efficiency to component performance, cooling air consumption and other parameters. Based upon these studies, a power plant designated "ATS50" evolved which will be consistent with materials and other technologies which can be captured by an industrial, stationary gas turbine system typical of Solar's past and current offerings.

Early in the execution of Task 6 - System Definition and Analysis - it became apparent that the intercooled and recuperated (ICR) gas turbine selected in Task 3 was not the ideal candidate for development and field test in Phases III and IV of the DOE's ATS program. The following factors influenced this change in direction.

- The DOE's Solicitation for Cooperative Agreement Proposal (SCAP) specified a 60 month program culminating in commercialization of an "industrial" ATS in the year 2000. Preliminary studies of a development program indicated that an ICR gas turbine could not be developed to the point of commercialization in that time frame. It would have been better suited to the DOE's original schedule of commercialization in the year 2002.
- The ICR's thermal efficiency of 50 percent far exceeds the ATS program goal of a 15 percent improvement over current industrial gas turbines. 50 percent is actually 43 percent greater than the current base of 35 percent.
- The Market Study of Task 5 provided the following input that indicated against the ICR as the best choice for early commercialization of an industrial ATS:
 - The gas turbine marketplace can be characterized as "risk-averse." This term describes a reluctance on the part of gas turbine users to accept major technological changes that are not validated by substantial operational experience in their application. Features of the ICR that fall in this category include the very high (for an industrial gas turbine) firing temperature of 2500°F, the presence of a liquid cooled intercooling system with its associated liquid handling equipment, and the complexity of the engine control system. Such a reluctance to accept unproven technologies would limit the ATS to relatively few specialized applications. Thus the benefits of an ATS to the nation's economy, energy supply and environment would be both delayed and diminished.
 - The presence of "Availability" (which includes reliability) at the top of the list of desired characteristics of gas turbine systems argues against the complexity of the ICR as well as against the requirement for fuel gas compression up to the pressure required for the ICR cycle.

- The Market Study indicated a strong future demand for an ATS of approximately 5MWe capacity. Two characteristics of the ICR argue against its use in this small size:
 - The very high specific power of the ICR will result in extremely small size of airfoils in the high pressure regions of both the compressor and the turbine. This raises their cost in both components and, in the turbine, makes a robust cooling design quite difficult.
 - The relatively higher cost of the ICR system will render it less competitive to other technologies in this small size. Its specific cost (dollars per kilowatt) will be more competitive in larger sizes.

These arguments were presented to Solar's ATS Phase 2 COTR and to other members of the DOE-METC staff in a special briefing at Morgantown on July 28, 1994. Task 6 - System Definition and Analysis - was then re-directed toward the description of a less complex, optimized recuperated gas turbine as described later in this report.

SECTION 4

TASK 4 - CONVERSION TO A COAL-FUELED ADVANCED TURBINE SYSTEM (CFATS)

Originally scheduled to begin approximately two months after the start of Task 3, the actual start of detailed Task 4 work requires that somewhat accurate definition of combustor inlet conditions be provided. Such definition was not available during the process of optimizing the ATS50 power plant until near the end of Task 3. As the power plant definition transitioned from Task 3 to Task 6, the Market Study of Task 5 brought new input as to the probable characteristics of a marketable ATS cycle. Since the intent of later phases of D.O.E.'s ATS program is to build and demonstrate gas fueled power plants, there is no downstream impact of delayed performance of Task 4.

The goal of Task 4 is to study the conversion of the Gas-Fueled Advanced Turbine System (GFATS) to a Coal-Fueled Advanced Turbine System (CFATS). This conversion capability would allow the choice of natural gas or coal, based upon availability, cost, or other considerations. As stated in the proposal, the approaches to this conversion range all the way from the utilization of coal gas to direct firing of coal either as a dry powder or as a slurry with water or oil.

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

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

Further examination of the Direct Firing and PFBC technologies show that the solid material produced by them will result in an unacceptable level of plugging of the recuperator gas-side passages. There is at present no clean-up device available that will adequately protect the recuperator from such fouling. This leaves gasification as the only practical approach for use with a modified ATS combustion system.

Preparation of the Task 4 Topical Report is now under way. Also, at the request of DOE-METC, Solar is preparing a paper based on coal-fired ATS work for presentation at the 1996 ASME IGTI Turbo Expo.

SECTION 5

TASK 5 - MARKET STUDY

5.1 APPROACH

In the course of laying out the program for the Phase II Market Study Report, Solar's ATS Program Management selected two separate market researchers to conduct independent studies of the potential ATS Markets. One was to conduct an in-depth market analysis following an outline structured from the ATS Statement of Work under Contract with Solar (Part III, Section J, Attachment A, Scope of Work). The other was asked to provide an analysis using the same outline as a guide, but to approach the market study with greater latitude in scope and format.

Resource Decision Consultants (RDC) was selected to support Solar's ATS program and the market study as the principal market research firm. RDC was submitted as a selected contractor to the Dept. of Energy, and was approved for placement on the program. The Task 5 Topical Report contains elements of RDC's report, including a section describing RDC, and a brief biographical detail on Dr. Jim Williams.

Onsite Energy Corporation (Onsite), was selected to conduct market research from a different background and perspective. Onsite's principal investigator, Mr. Keith Davidson, has an extensive background in the natural gas industry, and has focused on commercialization strategies for emerging gas markets. Onsite was submitted as a selected contractor for the Market Study, and was approved by the DOE. The Task 5 Topical Report contains elements of the Onsite report, including a section on the company and Mr. Davidson, the principal investigator.

In the early months of Phase II, Solar conceptualized a system configuration based on an intercooled, recuperated turbine engine. While this configuration was chosen to begin the effort of analyzing the ability of the system to meet the technical goals of the DOE's Program, Solar instructed its marketing staff to provide feedback on the acceptance in the market place of such a size and cycle.

The researchers, in the course of their study, contacted many potential customers. Solar, drawing on 30 plus years of commercialization, identified drawbacks to the cycle and size initially selected. With the use of the Quality Function Deployment (QFD) analysis methodology (Figure 2), as well as application of the Pugh Chart (Table 1), Solar developed a set of matrices that took into consideration the DOE's Program goals, the customer's buying criteria, and Solar corporate objectives, to alter the selected system to more closely align with the market requirements. Ultimately, the optimized recuperated cycle was selected as the ATS most closely aligning with the market requirements without compromising the ATS Program goals.

5.2 ATS MARKET APPLICATION

5.2.1 Electrical Power Generation

The ATS can be used as an electrical power generation system to meet the requirements of electric utility customers. The market is generally defined by the types of electrical generators, such as: investor-owned utilities, municipal utilities, rural electric cooperatives, and independent power producers.

Figure 2. QFD Chart

Table 1. Pugh Chart

CONCEPTS	CRITERIA									
	S.C. High TIT/P.R.	Intercooled S.C.	Recup Cycle	ICR Cycle	Humid Air Cycle	S.C. + Reheat	Chem. Recup	ICR + Reheat	Steam Inf. S.C.	
Low Emission	+	+	+	+	+	+	+	+	+	
High Efficiency	+	+	+	+	+	+	+	+	+	
Low Lifecycle Cost	+	+	+	+	+	+	+	+	+	
Low First Cost	+	+	+	+	+	+	+	+	+	
High Power Rating	+	+	+	+	+	+	+	+	+	
Low Risk - Schedule	+	+	+	+	+	+	+	+	+	
Low Risk - Technology	+	+	+	+	+	+	+	+	+	
Low Risk Cost	+	+	+	+	+	+	+	+	+	
High RAMD	+	+	+	+	+	+	+	+	+	
Spinoff Technology	+	+	+	+	+	+	+	+	+	
Fuel Flexibility	+	+	+	+	+	+	+	+	+	
Strategic Fit	+	+	+	+	+	+	+	+	+	
Tech. Integration	+	+	+	+	+	+	+	+	+	
Cost Acceptance	+	+	+	+	+	+	+	+	+	
Total +s	0	8	8	8	8	8	8	8	8	
Total -s	0	8	4	0	7	8	2	7	8	

Note: Baseline is 1994 S.O.A. Industrial Gas Turbine System

Page 10

The ATS can be applied in both traditional (baseload and cycling) setting, and the most recent development, distributed/dispersed generation applications. As electricity peak demand continues to grow at or above the nation's Gross Domestic Product (GDP) through the remainder of the decade and beyond, this trend will create major opportunities for the ATS due to its strategic application as well as its high efficiency, low capital cost, short installation lead time and compliant environmental emissions.

5.2.2 Oil and Natural Gas Production, Transmission and Storage

The largest existing market for the ATS includes Solar's traditional gas and oil pipeline and storage industries, including production and processing as well as transmission and storage companies. This industrial segment will be growing in response to increasing worldwide demands for energy and fuel. Hence, these oil and gas sectors, which depend extensively on pumping equipment and systems, represent clear opportunities for the ATS with a capacity between roughly 1,000 and 40,000 hp. With a high-efficiency level of around 43 percent, a low capital and maintenance cost, coupled with compliant emissions performance, the ATS is a very competitive option for the oil and natural gas industries.

Deregulation is occurring much more slowly in the gas production segment. However, as a result of the pipeline deregulation, local gas utilities and large users increasingly deal directly with gas producers to obtain their supplies. Deregulation has also placed pressure on increased operating efficiency and cost reduction. Reducing maintenance and energy costs, and the use of remote operation will become important management and operation goals within the gas industry.

The increasing difficulty of environmental compliance is a key issue facing the pipeline industry. Regulations regarding exhaust emissions (primarily NOx) and noise are making environmental compliance a major hurdle, which has essentially become a go/no go issue in driver/compressor purchasing decisions. There is some sentiment within the industry that electric drives may be the only practical solution to some siting problems.

5.2.3 Industrial Prime Movers

The industrial sector accounts for more than 36 percent of total end-use energy consumption. Process heat accounts for the largest share of energy consumption in industry overall, and mechanical shaft drive represents another large use of energy in many industries. This sector represents a significant opportunity for the ATS.

In particular, the ATS is well suited to industries with requirements for steam. If an industry requires high process steams, the ATS provides the same air flow for high pressure steam and can be turned down without compromise to its electrical efficiency.

The ATS can be used for industrial manufacturing power generation to meet on-site plant requirements, including mechanical shaft power for compressors, and pumps in petrochemical and other process energy intensive applications, and in electric/thermal cogeneration to serve a portion of on-site electric and process steam demands in manufacturing plants depending extensively on low-cost, reliable electricity supply.

In cogeneration applications, the recuperated ATS is best suited for industries with low thermal requirements because of its very high electrical efficiency. Since its combustion gases are relatively low in energy, the ATS is best suited to industries with a high ratio of electric energy needs to thermal energy needs (E/T ratio).

5.2.4 Marine Propulsion

A market segment that has recently emerged with a potential for the ATS-size power system is high speed craft propulsion. While the shipping industry overall has not grown substantially in recent years, the high speed segment has demonstrated strong vitality and growth.

Prospects for future growth remain strong as the increasing speed and ride quality of today's fast ferries make them very competitive with other forms of surface transportation and short haul airlines. The growth of passenger vessels has been especially strong in developing countries in the Asia-Pacific Region. Larger, high speed vehicle and passenger ferries have shown strong growth in northern Europe, the British Isles and the Mediterranean.

5.3 MARKET REQUIREMENTS

Representative input from these market segments states their requirements as follows (in order of importance):

- Availability, a function of reliability, durability and maintainability.
- Emissions
- Customer Support
- Fuel Efficiency
- Life Cycle Cost
- First Cost
- Project Execution
- Financing

These requirements were balanced against various possible ATS product characteristics in a QFD analysis in order to arrive at the system defined in Task 6.

5.4 COMPETING TECHNOLOGIES

Within the utility, industrial, commercial/residential, mechanical drive and transportation markets, the industrial ATS will compete with the technologies shown in Table 2 together with their key characteristics.

5.5 METHOD AND RESULTS

Using projected growth of the markets identified for ATS, together with market variables such as fuel price, Solar and the two subcontractors constructed a model of the marketplace out through the year 2020. This model was subjected to a Monte Carlo simulation of prospective ATS applications played against the key characteristics of Solar's ATS and those of the competing technologies shown in Table 2. The Solar ATS used in the simulation is the optimized recuperated gas turbine defined in Task 6 - System Definition and Analysis.

Table 2. Competing Systems for Electrical Generation¹

System	Availability (%)	NOx Emissions (ppm)	Installed Cost (\$/kW)	Thermal Efficiency (%)
ATS	96	3	620	43.2
ATS + HRSG	98	3	1000-1100	up to 74%
Simple Cycle Aeroderivative	92	25	716	39
Simple Cycle GT Heavy Duty	92	25	558	28.7
GT-Combined Cycle	92	9	700	58
GT-Chem Reactor/Reheat/Inter-cooled	90	<1	850-1000	37.2
Storage Battery (5 hour)	91	0 ²	804	24.2
Gas Boiler/Steam Turbine	95	25	680	25
Conventional Gas Turbine	95	25	650	24.5
Phosphate Acid Fuel Cell	91.6	Trace ²	2000	41.1
Molten Carbonate Fuel Cell	97	Trace ²	3000	52.9
Reciprocating Gas Engines	91	42	606	39
Steam Injected Gas Turbine	92	5	850-1000	37.9

¹ Some data from EPRI Technical Assessment Guide.

² Does not include all emissions at other sources.

The first outcome from the Market Study was that current users and potential customers expressed interest in two sizes, 5 MWe and 15 MWe. A third and lower peak was observed at 10 MWe. This information was relayed to the Task 6 ATS preliminary design process and resulted in the plan to develop a 5 MWe ATS that could be geometrically scaled upward to the 15 MWe size.

Final iteration of the Market Study based on characteristics of the two sizes of ATS product defined in Task 6 resulted in the following forecast for the year 2020:

- 26,880 MWe (36 million horsepower) of Solar ATS power will have been installed and commissioned.
- A total of 0.82 quadrillion BTU of fossil fuel will have been saved worldwide. This compares fuel consumption with that of an energy economy that would have developed on its own without the DOE/Solar effort.
- Worldwide emissions of NOx will have been reduced by 343,000 tons per year, again compared to a future without a DOE/Solar ATS.
- Exploitation of the ATS opportunity defined by the Task 5 Market Study will have provided over 7000 new jobs at Solar, its suppliers and at user locations.
- Reduction in the cost of the energy used in the production of U.S.-manufactured products will reduce the cost of these products and make them more competitive in a worldwide marketplace.

A Topical Report covering the Task 5 Market Study was submitted to the DOE in final form on May 11, 1995.

SECTION 6

TASK 6 - SYSTEM DEFINITION AND ANALYSIS

6.1 SYSTEM SELECTION

In their report to the Congress the Department of Energy has stated four primary goals of the Advanced Turbine System (ATS) Program. These are:

- Energy conservation: Thermal Efficiency 15 percent greater than current gas turbine systems.
- Clean air: Less than 10 parts per million of NOx and less than 15 ppm of CO and unburned hydrocarbons.
- Cost of Electricity: total (lifetime) cost of power to be at least 10 percent lower than with current systems.
- Reliability: Reliability, Availability, Maintainability and Durability (RAMD) now lower than with current systems.

In addition, The DOE's Phase III and IV SCAP requires that the proposed ATS be capable of completing development, including a field evaluation, and be ready for commercial introduction by the year 2000.

Task 3 identified an intercooled and recuperated (ICR) gas turbine cycle as the ultimate system to meet the four primary goals stated above. Referring to this system as Option "A", Task 6 developed an Option "B" which addresses near-term issues such as development cost and marketability. Briefly comparing these two options:

	Option "A"	Option "B"
Gas turbine cycle type	ICR	Recuperated
Thermal efficiency (ISO, LHV @ engine shaft)	50%	45%
Engine overall pressure ratio	16:1	9:1
Firing temperature (TRIT), °F	2400-2600	2100-2200
Emissions, ppmv NOx/CO and UHC	<10/<15	<10/<15
Reduction in cost of electricity	>>10%	>>10%
RAMD	Good	Better
Development cost	High	Moderate
Deliverable by AD 2000?	No	Yes

Both options are seen to meet all program requirements except for the requirement for commercialization by the year 2000. This Task 6 Topical Report develops Option "B" as a viable near-term system that will maximize early ATS benefits while the Option "A" concept and the ATS marketplace are given time to grow with each other

6.2 CONCEPTUAL DESIGN

The proposed layout for the recuperated cycle ATS design is shown in Figure 3. In essence, it consists of a new nine stage compressor feeding a catalytic combustor and a new turbine: a single stage gas producer (GP) turbine and a two stage power turbine incorporating a variable area cantilevered nozzle (VAN). The catalytic combustor shown in the figure is one of two main combustor options: it may be considered replaceable with an ultra-lean premix combustor, along with some minor casing modifications. Each of these design elements will be described later in more detail.

Figure 3. Solar's Advanced Turbine System (Cross-Section)

Marketing studies carried out in Task 5 identified two strong demand peaks, and as a result, the aerodynamic conceptual design incorporated the advantages of scalability to the final ATS selections. ATS component development will concentrate on the smaller machine with results scaled up to the larger. This approach conserves program cost and energy input to prototypes and will provide some incremental performance to the larger machine through economies of scale. These scaling laws operate as follows on gas turbine rotating hardware:

- For constant rotor linear tip speeds, geometrically similar components will operate with
 - identical pressure ratios
 - identical efficiencies
 - identical stresses
 - comparable metal temperatures

- Rotational speeds will scale inversely proportional to linear dimension
- Air flow and power will scale with the square of linear dimension

Heat transfer components such as recuperators or cooled airfoils will scale differently because the heat flux at any given location will vary with the cube of linear dimension and the size of the heat transfer path scales with its square. This does not affect the application of the rules for scaling aerodynamic components; heat transfer designs will be 'thermally' similar but geometrically dissimilar.

Scaling is not applied to standard hardware such as fasteners and tubing. It may also be intentionally set aside where performance advantages are available in the larger scales through relatively reduced airfoil loading and trailing edge thickness, and wall clearances and surface finish.

Based on component and cooling technology similar to that used for the ICR option, an optimized recuperated gas turbine will demonstrate approximately 45 percent thermal efficiency at a modest 9:1 overall pressure ratio when fired at 1180°C (2150°F) TIT. Studies have shown that these levels of pressure and temperature will find a more rapid acceptance in the marketplace than the 18:1 PR and 1340°C (2450°F) TIT optimized ICR. There is also an attractive risk reduction due to the fact that only one half point of thermal efficiency is traded for the reduced firing temperature. This will allow continued usage of the well-proven Type 347 stainless steel as the recuperator sheet in the event an alternate material delayed its development process.

The rotor bearing system is based on proven industrial turbine practice, with fluid element bearings in all locations (radial and thrust). Fluid element bearings were chosen for their high durability and tolerance to variations in oil cleanliness and buffering system operating pressures. The gas producer rotor runs in three self-aligning tilting pad radial bearings with a tilting pad thrust bearing and the power turbine is a two bearing overhung design also with a tilting pad thrust bearing. Both thrust bearings are accessible for field replacement if necessary. A tapered joint system similar to the current Solar products connects the compressor aft hub to the GP shaft. The surface speed of the bearings will be slightly higher than current engine experience, but is not expected to present any design challenges.

6.3 RECUPERATED GAS TURBINE CYCLE CHARACTERISTICS

With the firing temperature (TRIT) of a recuperated gas turbine fixed by the material and cooling system selected for the stage one turbine airfoils, maximum thermal efficiency will be found to occur at an optimum pressure ratio. Below this optimum, pressure ratio itself rules and is too low to provide useful efficiency from the core engine itself. Above this optimum, recuperation will be reduced by a decreasing differential between compressor discharge temperature and the temperature of the exhaust gas leaving the expansion turbine(s).

Beyond the firing temperature limit imposed by the turbine material and cooling technology, a secondary limit is presented by the exhaust temperature that the recuperator material will withstand.

The optimum efficiency for a recuperative cycle, based upon technology consistent with the program time frame occurs between PR's of 7.5:1 to 8.9:1 and TIT's of 1121 to 1238°C (2050 to 2260°F). Solar selected the higher PR because of its increased potential for growth. In particular, sensitivity studies indicated benefits of higher PR cycles are enhanced to a greater degree by cooling flow reductions and increases in TIT, both of which will be achieved during the program through improved materials and hot section cooling technology. Component material and cooling strategy selection

plays a key role in the selection of the design point, as shown in Table 3. The highest overall thermal efficiency is not achieved at the highest TIT in the range, but by the configuration that most efficiently uses the range of material, cooling, cycle, and mechanical design options available.

Table 3. Range of TIT, Cooling and Efficiency at Selected PR for Solar's ATS

Configuration	TIT °C (°F)	PR	Efficiency (ISO, LHV, No Losses)	Total Cooling	Limiting Component
All metallic	1204 (2200)	8.92:1	43.1 %	13.3 % W_{a^*}	347 SS Recuperator
Metallic/Ceramic	1185 (2166)	8.92:1	45 %	9.7 % W_{a^*}	347 SS Recuperator

*Engine inlet airflow

Further "fine-tuning" of this cycle will take place during the final design of Solar's ATS as detailed component performance parameters are established.

6.4 ATS COMPRESSOR

The ATS compressor (Figure 4) will be scaled directly from several stages of the Solar Advanced Component Efficiency (ACE) compressor. The goal of the compressor portion of the Solar ACE program is to design and develop a state-of-the-art multistage axial flow compressor which can be used in the next generation of simple cycle and recuperated industrial gas turbines. The ACE compressor is a 15-stage axial design with a pressure ratio of up to 20:1 and adiabatic efficiency of 87.6 percent. The compressor is being designed using all of the latest aeroengine design tools and technologies. Moreover, without the obvious envelope and weight constraints of aircraft engines, the ACE compressor will have design goals of lower cost and improved ruggedness. For those reasons it has light aerodynamic loading for high efficiency, low aspect ratio blading and long blade chords for ruggedness and low cost (fewer blades in each stage).

The ATS compressor incorporates the first 9 stages of the 15-stage ACE compressor. The ACE compressor is being designed for 29.3 kg/s (64.5 lb/s) airflow rate to fit the compressor rig to be used for testing. It will then be scaled appropriately for the ATS engine. Table 4 compares the ATS compressor with the Taurus 60 baseline. ACE airfoil types have already been demonstrated in the 1994 uprate of the Mars 100 gas turbine.

Figure 4. ATS Compressor

Table 4. ATS Compressor Performance

Parameter	ATS	Taurus 60
Corrected Airflow kg/sec, (lb/sec)	16.2 (35.7)	20.2 (44.5)
Pressure Ratio	8.92	11.5
Adiabatic Efficiency (%)	88.51	86.0
Corrected Rotational Speed (rpm)	19,244	15,000
Number of Stages	9	12

6.5 ATS RECUPERATOR

The ATS Primary Surface Recuperator (PSR) is a compact design that provides high effectiveness, moderate pressure drop and long life (Table 5). The construction is rugged and the modular nature of the design gives it superior flexibility to handle thermal stresses. It is made of 0.08-0.12 mm (0.003-0.0045 in) thick sheets of type 347 stainless steel (SS 347) folded into a corrugated pattern. This pattern maximizes the primary surface area that is in direct contact with exhaust gas on one side and compressor discharge air on the other. Pairs of these sheets are welded together around the perimeter to form air cells (Figures 5 and 6), the basic building block of the PSR. Each air cell is pressure checked before it is welded into the recuperator core assembly (Figure 7). There are no internal welds or joints within the air cell.

The PSR has been extensively analyzed using a model which are described later in the Subtask 8.1 Topical report. The effectiveness of the ATS recuperator for the cycle conditions was calculated from the model to be 90%, with an associated pressure drop of 2.5%. To satisfy ATS requirements, the model predicted a recuperator core of 2667 cells, representing an overall length of 249 inches. Alternatively, two cores at 124.5 inches could accomplish the same goal.

Table 5. ATS Recuperator Performance

Feature*	Recuperator Technology			
	Solar's PSR	Compact Plate Fin	Traditional Plate Fin	Shell and Tube
Relative Volume	1.0	2.8	7.6	11.8
Effectiveness, %	>90	87	79	84
Installation Flexibility	High	High	Moderate	Low
Thermal Mass	Low	Medium	Medium	High
Warmup/Cooldown Cycles	No	Yes	Yes	No
Required Maintenance	Low	Medium	Medium	High
*Based on 10 MW installations.

Figure 5. Primary Surface Sheets

Figure 6. PSR Air Cell

Figure 7. PSR Core Assemblies

The Solar PSR design is inherently resistant to low cycle fatigue (LCF) because it flexes to relieve stresses whereas the typical rigid designs, including plate-fin, tend to concentrate stresses at critical locations. High cycle fatigue (HCF) has not been a problem for the PSR due to its inherent damping characteristics. The stacking of cells in the PSR results in multiple friction interfaces for energy absorption. These characteristics also provide excellent exhaust sound suppression.

Solar has had extensive experience with various recuperator technologies, including tube-and-shell, brazed plate-fin, and PSR's. During the 1970s, Solar's industrial gas turbines were delivered to customers with tube-

and-shell and brazed plate-fin types of recuperators. A high percentage of these types of designs failed to meet users' expectations. The plate-fin is joined by brazed joints severely limiting repair options. In addition, the braze joints in the plate-fin usually suffer from dissimilar metal corrosion problems which are aggravated at high temperature. As a plate-fin recuperator increases in size, it becomes less capable of handling thermal transients.

PSR's present several major advantages over plate-fin and tube-and-shell type recuperators. They are smaller and lighter, have better performance, improved reliability and maintainability, and are scalable without sensitivity to thermal transients.

6.6 ATS COMBUSTOR

Traditionally, the broad goal in gas turbine burner development is to maximize combustor loading within specified constraints. This approach serves to reduce burner size and material cost. In addition to cost, reduced burner size acts to reduce the surface area that must be actively cooled. Typical constraints imposed upon a gas turbine combustor include:

- minimum acceptable combustion efficiency

- adequate operating range
- acceptable combustor liner temperatures and temperature gradients
- acceptable pressure drop
- maximum acceptable pattern factor
- sufficiently low emissions
- acceptable dynamic pressure variations

Thus the design goal of an ultra-low NOx combustor is to maximize combustor loading but with the more stringent constraint of ultra-low NOx emissions. These low NOx emissions are achieved by reducing the combustor primary zone equivalence ratio (ϕ), and subsequently, the temperature. The lower temperature results in lower NOx formation rates. However, the reduction in temperature also lowers the combustor loading that can be achieved within specified combustion efficiency constraints. Consequently, an ultra-low NOx combustor is a larger, less heavily loaded unit than a conventional burner.

The need to reduce combustor loading to maintain combustion efficiency when equivalence ratio is reduced is illustrated in Figure 8. This figure depicts a typical gas turbine combustor performance map and typical design points for a conventional burner and a low NOx emissions combustor employing lean-premix combustion. As allowable combustor loading decreases, the combustor must be made larger to achieve the same combustion efficiency. The larger burner may lead to combustor cooling challenges because of the larger surface area required to be cooled. This issue is of particular importance with recuperated engines having high combustor inlet temperatures.

Figure 8. Representative Combustor Performance Map

The selection of a combustion technology for ATS was influenced strongly by the goals of reducing NOx emissions to 8 ppm initially and 5 ppm ultimately. These goals are compared with Taurus 60 baseline in Table 6. Solar has selected catalytic combustion and ultra-lean premixed combustion (ULP) as the technologies with the highest probability of achieving these goals within a time frame consistent with the program schedule.

Laboratory testing of catalytic reactors has demonstrated NOx levels below 5 ppm. Internally funded and Phase 2, Task 8.2 and 8.5 work has already demonstrated the viability of Solar's catalytic approach. However, significant challenges remain in applying catalytic combustion to an industrial gas turbine. To ensure timely commercialization of ATS, Solar will develop ULP combustion systems in parallel with the catalytic combustion system. Technology advances in the areas of premixing, variable geometry controls, and advanced combustor cooling will allow ultra-lean premixed operation at NOx levels of 8 ppmv.

As a backup to the catalytic combustor (Figure 9), development, an ULP system will be developed in parallel path in the event that catalytic system development time exceeds expectations. The selection of the combustion technology for the ATS demonstrator will be made approximately one year after the start of Phase 3. In the event catalytic combustion is not deemed ready for the demonstrator, catalyst development can continue and the technology will be incorporated in the retrofit engines.

Table 6. ATS Combustor Performance

Emissions at 15% O ₂ , Dry, ppmv	ATS		
	Baseline (Solar Taurus 60)	ATS	Change
NOx	42	5	- 88%
CO	50	10	- 80%
UHC	25	10	- 60%

The ULP combustion system (Figure 10) will build upon Solar's lean premixed combustion technology (SoLoNOx) that was recently introduced to the gas turbine market (Figure 11). Lower NOx emissions are achieved by operating the combustor primary zone at a lower average temperature (leaner). In addition, pre-mixing the fuel and air before combustion avoids large temperature excursions from the average temperature within the primary zone. These hot spots are traditionally identified as significant NOx sources in gas turbine combustors.

Figure 9. Engine Cross-Section Showing Can-Annular Catalytic Combustor

Figure 10. ATS Ultra Lean Premixed Combustor Approach

The major elements of the ULP system are the combustor liner, the fuel injector, and the variable geometry system. The combustor liner is similar to a conventional combustor in terms of general geometry but is larger in volume to allow complete combustion at lower flame temperatures. The liner preliminary design employs conventional high temperature sheet metal construction. Advanced cooling techniques beyond traditional film cooling are employed to maintain acceptable liner wall temperatures. The design combines convection/impingement cooling and effusion cooling. Selective use of ceramics will be considered to mitigate liner cooling requirements. Ceramics are also expected to help reduce CO emissions

by preventing flame quenching in the liner boundary layer. Tests in the DOE/Solar CSGT program will guide the application of ceramics in the ATS combustion system.

Figure 11. SoLoNOx Combustor Liner (left) and Fuel Injector (right)

6.7 ATS GAS PRODUCER TURBINE

The design challenge associated with the ATS turbine is to maximize efficiency while satisfying both the life cycle requirements and a required cost objective. Industrial turbine design requirements are driven by high cycle fatigue (HCF) life, cost, and performance. Industrial turbines can benefit from low work stages with more lightly loaded airfoils because of the absence of weight and size restrictions. However, this is limited by the drive to reduce parts count and in the case of cooled stages the need to reduce cooling flow. The life requirements of industrial turbines require moderate wheel speeds, higher cooling flows or reduced TIT, and thicker airfoils with higher losses.

The solutions to these challenges were found in the configuration and material selection. Recuperated engines show optimum performance at lower pressure ratios and TIT. The lower pressure ratio combined with the new more efficient compressor allowed all the work to be done in a single-stage GP without substantial decrement to turbine efficiency. This, combined with the lower TIT, reduced the amount of cooling required. Cost of the turbine also benefited through the reduction in parts count by eliminating one cooled stage. The cycle efficiency benefited from the use of ceramic blades and thermal barrier coatings (TBC's) on the vanes and endwalls. The tip clearance of the ceramic blade must be close to that of the metal blade to realize the performance improvement of the reduced cooling. The power turbine may benefit from the use of brush seals on the blade tip. Brush seals will decrease tip losses to that of a shrouded blade without the increased airfoil stresses that typically require a wheel speed and or annulus area reduction.

Table 7 contains a comparison of the ATS to the industry baseline. This table indicate the performance advantages of the ATS turbine over the baseline industrial turbine.

Table 7. Comparison of ATS Gas Producer Turbine With Baseline

Gas Producer Turbine	ATS	Taurus 60
Pressure Ratio	2.45	3.69
Efficiency	0.891	0.874
TIT (°C)	1202	1028
% Cooling	6.92	7.67
Stage Count	1	2
Airfoil Count	74	184
Life (TBO) (hrs)	30,000+	30,000+
Overhaul Cost	Low	Low

The ATS turbine will use Solar's latest aerodynamic design techniques to achieve the efficiency goals of the program. A forced vortex solution will be employed to define the vector diagrams of this clean sheet design. The airfoil shapes will be optimized through the use of three dimensional viscous flow solutions.

The gas producer(GP) turbine will feature a single-stage, high work, low aspect ratio turbine. A high work stage was chosen over two low work stages to minimize the amount of cooled hardware and

therefore the cooling and associated efficiency penalty. Both options were investigated and it was determined that the loss in efficiency of a high work versus two low work stages was not as detrimental to the overall cycle as the additional cooling requirements. The GP stage will be designed with a low work coefficient (enthalpy-speed squared ratio: $\Delta h/U^2$) which produces reduced turning losses. The flow coefficient (radial flow-speed ratio: C_r/U) which represents through flow velocities will be minimized to reduce losses. These design philosophies require small throats and larger airfoil counts, because of this advanced manufacturing techniques must be employed to satisfy tolerance requirements.

The nozzle of the GP will benefit from end wall contouring. An initial contour, based on the Delch model will be optimized with the use of three dimensional viscous flow analysis.

The turbine design points including the optional power turbine for both engines are presented in Table 8.

Table 8. Performance of ATS Gas Turbines

Parameter	ATS		Baseline (Taurus 60)	
	GP	PT	GP	PT
Corrected Flow $W/\sqrt{\theta}$ kg/s (lb/s) δ	4.58 (10.08)	10.69 (23.51)	3.86 (8.49)	13.06 (28.74)
Pressure Ratio	2.45	3.18	3.69	2.78
Efficiency, %	89.1	90.5	87.4	88.3
Corrected Speed $N/\sqrt{\theta}$ (rpm)	8572.4	5615.9	7165.5	7689.8

6.8 ATS POWER TURBINE

The free power turbine (PT) consists of two lightly loaded stages for optimum efficiency, improving component efficiency by 2.2 points over the baseline shown in Table 9. This table contains a comparison of the ATS to the industry baseline. This table indicates the performance advantages of the ATS turbine over the traditional Solar industrial turbine. For optimum performance, the free power turbine (PT) consists of two lightly loaded stages which have higher work coefficients than the GP turbine, primarily due to the lower PT speed. From a design perspective, it may be desirable to minimize the transition duct between the GP and the PT in order to reduce complexity and duct losses and avoid having to support the duct with a number of struts. This "close coupling" of the power turbine, shown in Figure 12, provides a means to accomplish these goals, albeit with a small efficiency penalty due to compromises in flowpath geometry. (The flow coefficient design limits are driven by limits on the extent of flowpath divergence between the GP and PT). The flowpath divergence has been set at limits currently adopted by other industrial gas turbine designs and will require verification of clean end wall flow through 3-D viscous flow analysis.

Close coupling the power turbine may be accommodated by means of a rotating inner flowpath and a large diameter ceramic seal. Should these items prove too great a risk then the power turbine will be moved axially aft and radially outward. The inter-turbine duct will increase in length and a strut will be added resulting in increased losses. However, the power turbine efficiency will increase due to optimizing the geometry to the wheel speed requirements. The net result will be a decrement to the cycle predominately because of cooling required for the strut.

The first nozzle of the power turbine is variable to allow for better off-design performance by maintaining a constant TIT, providing an improved transient response for the recuperated engine, and allowing continuous ambient rematch capability. Variable nozzle losses due to leakage, steps in the flow path, and gap losses will be decreased by applying a button to the inside and outside diameter of the vane. The leakage losses can be further reduced by using spherical end walls on the nozzle.

Figure 12. ATS Turbine Configuration Showing 'Close-Coupled' GP to PT Transition Duct

Table 9. Comparison of ATS Power Turbine With Baseline

Power Turbine	ATS	Taurus 60
Pressure Ratio	3.16	2.78
Efficiency	0.905	0.883
TIT (°C)	900	689
% Cooling	3.29	2.43
Stage Count	2	2
Airfoil Count	218	156
Life (hrs)	30,000+	30,000+
Overhaul Cost	Low	Low

The diffuser was sized for optimum recovery with the area ratio and length of the diffuser based on the published work of Sovran and Klomp. The recovery was based on past diffuser data and the exit condition of the power turbine. Solar currently has an R&D program investigating the use of vortex generators to improve recovery which will be applied to the diffuser should this new application of this existing technology prove to be beneficial.

6.9 ATS CONTROL SYSTEM

The ATS system will be controlled by a Programmable Logic Controller (PLC) mounted on the driver frame. This offers several advantages over a conventional PLC located in a remote control console. It significantly reduces manufacturing cost by eliminating the voluminous wiring that connects the system and control console before and after production testing. The potential for wiring errors at the factory and the job site are reduced, equating to faster delivery and quicker installation and start-up times.

Interface between the package and the remote control console CRT will be achieved via a simple data highway serial link. The potential for wiring errors at the factory and the job site will also be reduced which equates to faster delivery and quicker installation and start-up times. Field wiring, from sources external to the ATS package, will be reduced since it can be terminated at the local PLC instead of being routed to a remote control console. Operator interface with the ATS package will be from a remote CTR providing both monitoring and control capability.

An uninterruptible AC power supply (UPS) will be used to protect those essential services on the ATS package in the event the primary source of AC power to the station motor control center is lost. The UPS system will eliminate the necessity for a separate 24Vdc control battery system. In addition to supplying emergency power to the AC lube oil pump for post lubrication, it will also insure adequate 24Vdc control power by means of an AC to DC converter. For both environmental considerations and personnel protection, the battery system will utilize valve-regulated, gas-recombination cells. Battery cells will be made of lead calcium which can be recycled.

The Solar gas turbine control system, Turbotronic®, typically includes a man-machine interface (MMI). Phase 2, Task 8.6 of the ATS program is developing expert system capabilities in the MMI to assist in analyzing and diagnosing problems of the turbine system.

6.10 ATS OVERALL SYSTEM DESIGN

In addition to the gas turbine engine, Solar's ATS system will consist of three major elements: driver frame, AC generator/reduction gearbox assembly and ancillary support frame. The driver frame includes the turbine engine start system, lube oil system, gas fuel system and on-board PLC. Figure 13 details the ATS subsystems and components and indicates their features and benefits. Figure 14 shows another view of the integrated package design giving more three dimensional detail to the air inlet duct, recuperator, and driven equipment.

CONTROLS AND ELECTRICAL

- Advanced MMI and control system for improved RAMD, reduced cost of power.
 - Remote Operation
 - Plant Load Management
 - Built-in Diagnostics
- On-site controls for improved RAMD, reduced cost of power.
 - Reduced Factory Wiring
 - Reduced Site Wiring
 - Simpler Commissioning
- Uninterruptible power supply (UPS) system to ensure availability in the event of loss of AC power.

FUEL GAS SYSTEM

- Integral loop powered, microprocessor controlled fuel valve positioner for accurate response and pressure control, increasing RAMD.
- Electric actuators, eliminating need for hydraulic system, improving RAMD and first cost.
- Commercial grade carbon steel piping for fuel transport, minimizing first cost.
- Stainless steel tubing for instrumentation lines (fuel and lube oil systems) for robustness of monitoring systems, improving RAMD.

ENCLOSURE

- Frame in structural steel for strength and durability, easy maintenance
- Acoustical panels on enclosure reduce noise signature; removable for full service access
- Side access doors for minor maintenance, verification of interior conditions during operation.
- Fire detection and suppression systems use environmentally-friendly consumables

DRIVER FRAME AND LUBE SYSTEM

- Carbon steel welded frame for structural integrity.
- 3 point mounting with integral lifting points for simplified foundation design, site installation, handling.
- Frame designed to contain oil spills and waste water for full environmental compliance.
- Oil storage sized to provide retention time to extend oil operating life, atmospheric vent to prevent over-pressurization.
- Oil demister located in vent to ensure removal of 99.9% of oil particles.

- Single cartridge type oil filters for up to 10,000 hours of cleanliness, flexible mounting options and ease of service.
- Variable frequency controlled oil pumps and cooler fans for:
 - Optimal oil supply pressure and temperature.
 - Minimum noise emissions.
 - Reduced cost, improved RAMD, reduced parasitic losses (no additional pump for pre/post-heats, elimination of need for pressure relief, temperature control, system relief valves and associated piping and instrumentation).

DRIVEN EQUIPMENT

- Epicyclic reduction gearbox
 - Compact, straight-line shaft arrangement, avoiding offset shaft problems.
 - High durability: designed for 100,000 hours minimum life, 30,000 hours TBI.
- Gearbox supported directly from generator frame
 - Reduces first cost: No support structure, easy alignment.
 - Improves RAMD: Shorter drive train without low speed output coupling or bearing.
- Horizontally split housings for ease of maintenance
- 4 pole generator manufactured to NEMA standards, totally enclosed, allowing outdoor mounting without enclosure, AC driven cooling fans for minimum noise and parasitic losses.

REF142426

Figure 13. ATS Subsystems and Features

Figure 14. View of Integrated Design Package

The primary considerations in developing the Integrated design for the GFATS power generation package were:

- (i) initial cost
- (ii) operating cost
- (iii) system reliability
- (iv) accessibility/maintainability
- (v) environmental impact
- (vi) manufacturability
- (vii) overall physical size and weight

These considerations are not listed in any specific order of priority since they each directly impact one another.

A Topical Report covering Solar's Task 6 activity was submitted to the DOE in final form on April 26, 1995.

SECTION 7

TASK 7 - INTEGRATED PROGRAM PLAN

Solar has prepared a Research, Development, and Test Plan that builds upon ongoing ATS Phase 2 work, as well as related research activities, to ensure attainment of all program goals in a timely manner. Solar has identified parallel path approaches for items considered to have relatively high technical or schedule risk. In addition, Solar has designed its test activities in a manner that incrementally tests components and subsystems before incorporation and test in the full ATS system, further reducing overall risk.

This RD&T Plan includes the following:

- Rig testing to ascertain that the performance characteristics of components meet ATS requirements. These include compressor, turbine, recuperator and combustor rig tests.
- Rig testing of cooling and sealing systems which will isolate the performance of these systems from the rest of the gas turbine in order to examine their performance and compare it with ATS design requirements.
- Advanced materials evaluation and testing.
- Engine testing to include evaluation of both mechanical integrity and aerodynamic and thermal performance.
- Performance testing of the integrated gas turbine system to include the control system, all support systems and the driven equipment.
- Durability/reliability and performance evaluation of the integrated gas turbine system (package) under realistic field conditions at a host site for a minimum of 8000 hours.
- A risk management plan based on highly successful Solar disciplines that include:
 - A New Product Introduction (NPI) system based on principles of teaming and concurrent engineering that has resulted in reduced time to market for new products.
 - The use of Quality Function Deployment (QFD) techniques to ensure that new product characteristics are in full support of customer needs and expectations.
 - The use of PERG (Prediction and Evaluation of Reliability Growth), a corporate (Caterpillar) technique that provides for early identification of problems and identifies the evaluation program required to validate problem solutions.

In recognition of the critical importance of successful commercial introduction of the ATS product and technologies, Solar has also designed a commercialization plan that encompasses all necessary

aspects of manufacturing, marketing, and servicing the new product. Solar's commercialization plan also envisions the spin-off of appropriate technologies, providing an early return on joint development funding, expanding the overall market opportunities and reducing marketplace risk associated with introducing new technologies.

This commercialization plan includes the following:

- A Technology spinoff plan which recognizes that many of the advanced technologies developed for Solar's ATS can be applied to the existing product line. This spinoff plan examines these technologies and will alert Product Engineering to possibilities for their application in improving performance, reducing emissions, reducing cost and otherwise improving Solar's non-ATS product line.
- A Market Readiness Plan intended to accelerate awareness of the need for ATS products, to continuously monitor emerging market requirements and to foster market pull during the market introduction phase. Specific activities will include customer surveys, customer roundtables and participation in technical conferences and seminars. Tools will include educational literature trade shows and presentations.
- A manufacturing readiness plan that will assure that Solar's ATS is producible at an economical cost and that adequate manufacturing processes and capacity will be in place to support the commercial introduction of the ATS.
- A Product Support Plan which will ensure that all customer services are in place at commercial introduction of the ATS. These will include trained field service technicians and commissioning teams, Solar-furnished operation and maintenance programs and training, and field service tooling as well as tooling for Solar's own overhaul facilities.

Solar has established systems and organizational structures assuring an efficient program control. These systems are designed to take full advantage of concurrent engineering and cross-functional teaming in order to reduce the development to production schedule and to reduce overall program costs. The Work Breakdown Structure and Organizational Breakdown Structure are set up in a manner ensuring the ability to assign responsibility for the performance of the contract to individual cost account managers to the subtask level; and the implementation of earned value accounting will enable effective performance measurement and management of the work.

These systems and structures include:

- An ATS New Product Introduction (NPI) team with full-time representatives from Sales and Marketing, Engineering, Manufacturing, System Integration, Finance, Business Development and Customer Services. This team is responsible to two sponsors - Solar's Corporate Products Committee and the United States Department of Energy.
- A detailed Work Breakdown Structure (WBS) and Schedule
- A dedicated Contract Administrator
- Procurement administration incorporating Purchasing and Material Requirements disciplines accustomed to operating in a competitive commercial environment.

- Cost Tracking and Cost Accounting systems that operate in accord with generally accepted accounting principles (GAAP) and meet all current DCAA requirements.
- Project monitoring according to an "Earned Value" system that measures performance against both budget and schedule.
- A quality assurance plan that includes control of equipment, control of materials, preservation of product development data, design reviews, and monitoring of teaming partners and subcontractors.

These systems and organizational structures are all ISO 9000 certified and have recently passed their re-certification requirements.

The Task 7 Topical Report was submitted to the DOE in final form on July 6, 1995.

SECTION 8

TASK 8 - DESIGN AND TEST OF CRITICAL COMPONENTS

The purpose of Task 8 is to perform advanced design and test work on technologies which are critical to the success of Solar's ATS. Starting such work in Phase II of the program will assure that sufficient progress has been made so that timely application of these technologies can be made in Phase III. This timing will also provide for early discovery of any technological barriers that may prevent application of the intended technology. Should such occur, timely transition to a backup technology can then be made.

As originally awarded, Solar's Phase II contract specified three subtasks within Task 8:

<u>Subtask Number</u>	<u>Title</u>
8.1	Low Pressure Drop Recuperator
8.2	Low Pattern Factory Combustor
8.3	Autothermal Fuel Reformer (ATR)

In December of 1993, discussions with the COTR led to Solar's preparation of a proposal for six additional subtasks:

<u>Subtask Number</u>	<u>Title</u>
8.4	High Temperature (Dual Property) Turbine Discs
8.5	Low Emissions Combustion
8.5	Total Plant Controls (Man/Machine Interface)
8.7	Recuperator Materials
8.8	Reheat Combustor Materials
8.9	Composite Ceramic Airfoils

Funding for these additional tasks did not become available until July of 1994, at which time Solar initiated the requisite review and update of costs. The contract was modified (Revision A004) to include these added tasks on September 27, 1994.

8.1 LOW PRESSURE DROP RECUPERATOR (SUBTASK 8.1)

The strategy of the Advanced Turbines Systems (ATS) program is to develop a new baseline for industrial gas turbine systems for the 21st century, meeting the buying criteria of industrial gas turbine end users and having growth potential as a product line. These criteria resulted in the selection of a recuperated gas turbine cycle. The eventual engine or engines that result will utilize Solar's Primary Surface Recuperator technology (PSR).

Solar's Primary Surface Recuperator (PSR) technology is based on 24 years of development and operational experience. This technology has typically been applied to relatively low pressure drop cycles having modest exhaust gas temperatures. One objective of the ATS program is to develop engines of much higher thermal efficiency resulting in engines that fire hotter and have higher exhaust gas temperatures. Other goals included lower emission, cost of power and improved RAMD. Recuperator life prediction, creep modeling and performance prediction become even more important factors in the design.

Performance has been predicted using an in-house analytical model of the PSR. The accuracy of predictions has been notably good at design point. However, with an engine like ATS where high efficiency is such a salient and vital feature, predictions must be of the utmost accuracy, especially over the broad operating range of the turbine. An influencing factor of these predictions is the validity of the empirical data the model uses. Performance data have been obtained for the candidate heat transfer surface. Furthermore, performance data were obtained on a scaled rig to provide the necessary data to validate and calibrate the analytical model. The pretest predictions of air-side and gas-side pressure drop were in very good agreement with the actual test results. The predicted effectiveness also agreed well with that actually determined by experiment. The PSR rig test indicates that, at ATS design point operating conditions, thermal effectiveness will be 90.3 percent versus a minimum of 90.0 percent required by ATS performance requirements. The test also predicts an overall (air and gas side) static pressure loss of 6.8 percent versus 7.0 percent maximum ATS requirement.

A flattened tube test was designed to determine dimensional changes of the PSR heat transfer surface profile after exposure. These data are to be used in the finite element creep modeling that is underway. The test was still in progress at the time this report was written. Data will be reported separately upon conclusion of the test.

Subtask 8.1 has been completed and a draft copy of the Topical Report was submitted to the DOE on July 20, 1995.

8.2 SUB-SCALE CATALYTIC COMBUSTOR RIG (SUBTASK 8.2)

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 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.

The subscale catalytic combustor rig entered the period covered by this report with NO_x emissions in the 5 to 15 ppmv range versus a 5 ppmv goal. In addition, CO and UHC emissions were completely out of control – in the 1000 ppmv range. The rig was modified to provide a longer – 10.5 inch versus 6.5 inch – catalyst bed and to improve fuel distribution across the upstream face of the catalyst.

The subscale rig was then operated with this longer bed. The earlier work had produced very low NO_x emissions (down to 4 ppmv) but apparently incomplete combustion resulted in CO and UHC emissions exceeding 100 ppmv. Increased bed length was selected to address this issue.

The longer catalyst bed was operated in the subscale rig at 115 psig catalyst inlet pressure and with the inlet temperature varied from 850°F to 1080°F. Stable catalytic combustion (i.e., the auxiliary

burner downstream of the catalyst bed is extinguished and the temperature rise across the catalyst is maintained) was maintained at catalyst inlet temperatures above 1020°F with the catalyst inlet air/fuel ratio (mass-based) between 39 and 45. Emissions results were worse all the way around than with the shorter bed. The bed was returned to the supplier, Engelhard Industries, for evaluation.

A second 10.5-inch long bed was obtained but testing was deferred until an unacceptable catalyst inlet velocity profile has been corrected. Further analysis of the earlier test results suggest that the fuel flow measurement may have been in error in that actual fuel flow was less than indicated. Before further testing, a new fuel control valve was installed in order to regulate fuel flow in so as to maintain a constant air/fuel ratio. The velocity profile problem was addressed through modifications to the fuel pre-mixer.

Measurements of the velocity profile of gases entering the catalyst were 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 15, 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 subsequent 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 15.

- 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 15).
- 2) The configuration labeled "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 was modified by including a 1.5 inch flow straightener upstream of the catalyst bed. This configuration is illustrated in Figure 16.

The data shown in Figure 15 indicates that all these configurations flattened the profile but the arrangement of Figure 16 provided the flattest profile at +11 percent peak-average. Based on these results, the combustion rig was modified to reflect the changes illustrated in Figure 16. 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.

Figure 15. Catalyst Inlet Velocity Profiles

Figure 16. Subscale Catalytic Combustor Test Rig Configured to Flatten Catalyst Inlet Velocity Profile

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

Figure 17. Catalytic Combustor Results

A series of combustion tests were conducted over a three day period, yielding the best results up to this point. 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 NOx 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 17. 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 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 was completed.

The subscale premixer was installed on a unique rig in order to measure the fuel distribution profile. Up to this point, fuel profiles have been based on measurements at six fixed locations in the catalyst inlet. In the "premixer rig" measurements were made with a six-probe rake, rotated in ten degree increments, to provide a much more detailed fuel profile. The fuel profile provided presently is suspected of having peaks and valleys not detected by the present fixed instrumentation array.

A six-probe sampling rake has been installed to measure the distribution of fuel concentration at the exit of the premixer. Preliminary measurements are consistent with earlier estimates of 10 to 20 percent variation in fuel concentration. Detailed characterization of premixing with the current injector is in progress. Further improvement in premixing is being pursued. A new design for fuel injection will be tested. The new design uses three injection holes with extension tubes in each hole to obtain better radial penetration of the fuel at injection. This is expected to result in flatter fuel profiles at the exit of the premixing section. Once satisfactory premixing is achieved, a new catalyst bed will be tested.

Detailed fuel/air concentration measurements were made at the exit of the premixer using the six-probe sampling rake. Measurements using the baseline fuel injection tubes used in earlier tests indicated a 43 percent peak to peak variation in fuel concentration. Injection holes on the fuel tubes were optimized to reduce the peak to peak variation to about 15 percent (rms/mean of 5 percent). A new fuel injector design with extension tubes to achieve better radial penetration, was also evaluated and a 15 percent peak to peak variation in fuel concentration was measured.

A catalyst bed was tested under non-ATS baseline operating conditions with the new injectors. Desired bed activity was achieved at low inlet temperatures and lean fuel/air concentrations. Local overheating of a portion of the catalyst prevented successful completion of the test. Development work in the sub scale rig will focus on improving fuel injection and premixing with several fuel injection schemes under consideration. Catalyst bed testing will resume after optimal premixing is achieved.

8.3 AUTOTHERMAL FUEL REFORMER (SUBTASK 8.3)

Steam-fuel reforming converts natural gas and steam to a high-hydrogen-content fuel. The reforming process requires heat to produce the steam-methane reactions. To accomplish the reforming reactions, parts of the parent fuel have to be burned to raise the temperature to approximately 1250- to 1500°F. This approach of burning parent fuel partially to supply reaction energy is known as the autothermal fuel reforming. The high-hydrogen-content fuel has a wider range of combustion stability than natural gas. Hydrogen is lighter and more reactive than the original fuel and it mixes better with the combustor air. The hydrogen in the combustible stream enhances the flame stability and speeds the burn rate through the combustion zone. It can be burned at much leaner (low flame temperature) conditions, producing lower NOx emissions. 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. The steam reformation of fuel can utilize the heat removed from the exhaust gas. Recovering the waste thermal energy in the form of steam and then converting it to hydrogen, thus "chemically recuperating" a gas turbine engine enhances the system efficiency.

Catalyst screening tests planned for the tube reactor rig were completed in the previous annual reporting period. The Autothermal Reforming Rig (ATR) rig was being fabricated at the beginning of the period covered by this report. In this, rig active catalytic materials will be deposited on the inner surface of the monolith channels to extend the contact area. The rig tests are designed to

investigate the combustion efficiency, emission levels, pressure drop, and flame stability. Hastelloy tubes are inserted through the ceramic refractory lining for inlet air paths. Preparation of the rig testing at the existing test facilities is under way.

Additional tests were performed with the existing equipment to evaluate sulfur tolerance on the autothermal fuel reforming catalysts. Fuel was mixed with hydrogen sulfide (H_2S) with a concentration of 200 ppm, compared to 1 ppm H_2S containing in the local natural gas. The initial test results indicate over 70 per cent of hydrogen produced with no deactivity on the testing catalyst. Regeneration of spent catalysts by steaming as well as study of the effect of a dual oxide absorbent for controlling sulfur poison are under way.

Additional tests of autothermal fuel reformation were conducted to evaluate the effect of a dual-oxide absorbent on the performance of the reforming catalyst. An absorbent consisting of zinc and calcium oxides was selected for removing acidic species (H_2S , HCl , etc.) in the raw natural gas and serving as a polishing step to ensure a constant quality of gas turbine fuel. The test results showed that fuel reformation produces a high hydrogen content of product gas under the absorbent steady-state operation. Testing continued to fully investigate the effects of absorbent on the catalyst active life and sulfur-poisoning control.

The ATR rig was completed, installed in the test cell and operated through a shakedown test. This rig will evaluate performance of an ATR under actual ATS operating conditions. An injector is used for the premixing of fuel and steam. A pilot combustor partially oxidizes the fuel to provide the heat required for preheating this mixture to reformation temperature. Following a mixing section, the reforming catalyst produces the high hydrogen secondary fuel to be burned in a post-combustor where its heat content and other characteristics can be determined.

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 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 18 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 100°F. 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 was 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 was monitored during the test.

	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%)				
N ₂	3.36	37.11	62.55	62.14
CH ₄	90.66	49.28	13.78	5.64
CO	1.43	5.15	22.21	22.82
CO ₂	1.60	0.46	1.46	9.17
C ₂ +	2.95	-	-	0.23

Figure 18. Temperature Readouts Monitored by Thermocouples

An initial test was conducted at reforming temperatures of 1300 to 1500°F and under operating pressures of 60 to 120 psig. Steam was injected at steam-to-fuel ratios in the 0.3 to 1.0 range and passed through a nickel-based reforming catalyst coated on a ceramic monolith. Results from the test are positive in that a stable burning of product gas was maintained and controlled with an easy ignition, moderate pressure drops and without the assistance of auxiliary fuel. Additional tests are required in order to demonstrate the low emissions and high thermal efficiency as steam and fuel chemically recuperate.

The ATR batch-tube reactor was modified and fitted with a liquid fuel pumping and pretreatment system. The rig is ready for conducting a long duration test under reforming conditions using diesel fuel.

Work on the autothermal fuel reformer under the Phase II ATS contract is being brought to a close. The task has achieved its primary goal of producing over 70 percent of hydrogen when reforming natural gas. The test results of the reformed product gas combustion showed an easy ignition, stable flame, moderate pressure drops and burning without the assistance of torch and auxiliary fuel. Additional test using liquid (diesel) fuel as the feedstock also resulted in generating 60 to 65 percent of hydrogen in the product gas stream. Meanwhile, these tests demonstrated the tolerance of high sulfur content in the liquid fuel. Preparation of the Topical Report is under way toward submittal in July.

Results of the Phase II test work on the autothermal reformation of natural gas and diesel fuel suggest that this process is a promising approach to the clean combustion of unusual fuels that normally present problems with meeting clean air requirements. Accordingly, work will continue at Solar funded by an internal R&D budget.

8.4 DUAL PROPERTY TURBINE DISC (SUBTASK 8.4)

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. This dual property disc technology has additional application in increasing the efficiency of Solar's current and future non-ATS product.

The approach will be to achieve a mechanical bond between a cast high temperature alloy (such as MAR-M-247) in the rim area with a conventional turbine disc alloy in the central hub. An initial statement of work developed with the subcontractor, Howmet, proposed to use Howmet's Vacuum Plasma Structural Deposition (VPSD) process for producing dual property discs. As the design definition of Solar's ATS progressed, however, it became apparent that the design required discs that were too large for this process.

The statement of work was then revised to define a program based on solid-to-solid bonding techniques such as hot isostatic pressing (HIPing). Activated diffusion bonding will also be examined with an early down selection between the two processes. Heat treatments compatible with both alloys will be determined and single point machining methods for the bonding couple will be developed, positioning the project for the first bonding trials. 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. Bonding trials will begin upon receipt of first article Udimet 720 hubs.

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.

Material procurement has been completed, bond-surface machining has been completed and the resulting surfaces characterized. The surface roughness and profile have been carefully documented on all of the subscale test articles since these are variables which may influence subsequent bonding. The surfaces were within expected tolerances, however, they were in the upper range due to the difficulty in machining these tough materials. The test articles have been delivered to Howmet's Wichita Falls Facility for Fluoride Ion cleaning prior to bonding trials. In addition, all materials required for shear bonding have been sent to Ladish Corp. for this process.

The stress analysis, life prediction and non-destructive evaluation (NDE) tasks for the dual-alloy disc have begun. Initially, it was planned for the required analytical and testing work to be completed by Solar Engineering under this contract. After preliminary analysis and identifying the scope of the problem, Solar has elected to collaborate with outside consultants to assist in this effort. Discussions with Southwest Research Institute (SwRI), a leader in this field, led to the submission of a proposal which fulfills the program objectives. The effort will entail a technology transfer of existing finite element codes and constitutive models developed under sponsorship of EPRI and the Nuclear and Aerospace Industry. The models will be tailored for the materials and configuration of the Solar disc design. Negotiations are underway to establish a contract with SwRI for this work. Dr. Graham Chell and Dr. Jerry Leverant will be the Program Managers at SwRI. The advanced stress analysis, life prediction and NDE techniques developed for the dual-alloy disc will have immediate application at Solar in the design of high temperature components.

Once all contractual details concerned with adding SwRI as a subcontractor are completed, new labor and cost plans will be submitted to reflect the exchange of Solar labor costs for subcontractor costs in Subtask 8.4. There will be no increase in total program cost associated with this change.

8.5 FULL-SCALE CATALYTIC COMBUSTOR RIG (SUBTASK 8.5)

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 catalytic combustor design being developed at the subscale level as described in Section 8.2 will be tested in a single-can, full-scale combustor rig. The combustor diameter will be increased to approximately 10 inches. The system will be representative of the full-scale engine design including a premixer, catalyst bed, post-catalyst combustor and an integral part-load injector situated along the centerline of the cylindrical combustor. The combustor will be operated over the full range of engine operating points including simulated start-up, idle, low load, and catalytic mode over 50-to-100 percent simulated engine load. System performance will be characterized through measurements of emissions, pressure loss, catalyst bed temperatures, combustor exit temperature profiles, and pattern factor to the extent possible. Catalyst beds will be supplied by Engelhard Corporation based on their designs being developed during subscale testing. This effort is an important next step in advancing catalytic combustion to engine readiness.

Design of the test rig has proceeded up to the point of detail definition of the combustor based on results from Subtask 8.2. These results have led to the conclusion that the full-scale combustor should have provisions for varying the air flow split between the catalyst, part-load injector and the dilution zone. This feature will be incorporated in the rig design.

Rig design will proceed up to the detail drawing stage based on current results from the sub-scale rig in Subtask 8.2. Completion of detail definition and procurement of these hardware items will be deferred until problems with the sub-scale rig are resolved. These problems are related to an unsatisfactory velocity profile of the gasses entering the catalyst bed and to providing sufficient post-catalyst volume to enable more complete CO burn out.

8.6 TOTAL PLANT CONTROLS (MMI) (SUBTASK 8.6)

Solar believes that improvements in gas turbine control systems are required in order to fully support ATS goals. Such a control system requires that a Man-Machine Interface (MMI) operate within a multi-tasking, multi-user environment. In this subtask, Solar will design and demonstrate such a system to include advanced human interface features, advanced networking capability the employment of expert systems, and low-cost, long-range communications capability. The systems will provide for easy customization to customer's unique requirements as well as for simple in-the-field reconfiguration.

Initial efforts entailed configuring Solar's Systems Engineering computers to work with the software required in developing the Man-Machine Interface (MMI). Writing of a design specification for the MMI was begun early in the program.

Next, the development operating system hardware and software was procured and installed. The ATS development Application Server sub-network was installed along with developer workstations for executing the proof-of-concept task. This equipment has been tested and the development of communication protocol between the Allen Bradley PLC and MMI is underway. Specification of software development standards has also begun.

The MMI data acquisition module was developed for the incumbent hardware, an Allen-Bradley microprocessor and the MMI test work station installed. Initial real-time meters routines, windowing techniques and real-time trending routines were developed. An initial database was constructed from MMI descriptors, scaling and memory identification. The latter includes routines to retrofit existing display systems.

The proof-of-concept task has been completed development of a design specification proceeded. In addition to the data acquisition module for an Allen-Bradley Programmable Logic Controller (PLC), another is being developed for a Modicon PLC. During the proof-of-concept phase, it was determined that the system resources required by the Graphical User Interface (GUI) would not allow some of the functions required for the ATS application. Evaluation of an alternate GUI requiring fewer system resources has been started.

Work now proceeded on the following long-term elements:

- The Application Programming Interface for the GMS (Graphical Modeling 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.

Three approaches to the Graphical User Interface (GUI) were studied. The original GUI, "Sammi," lacked features that had been promised by the vendor. An alternative GUI was poorly supported by the vendor. At first, Solar examined writing a GUI in-house, then further negotiations with Sammi resulted in a price adjustment and the addition of the promised features.

Work on dynamic graphics continued and efforts were begun on the operator menu and displays.

8.7 HIGH TEMPERATURE RECUPERATOR MATERIALS (SUBTASK 1.8.7)

Solar's Primary Surface Recuperator (PSR) is a compact heat exchanger that delivers high effectiveness with a low pressure drop in a compact volume. This design is readily adapted to engines of most any size, however, cycle conditions do dictate that material selection. To date, type 347 stainless steel has been the material of choice for nearly all applications due to its physical properties, fabricability and relatively low cost. Other materials can be used should a particular engine cycle demand it.

The primary failure mechanism for the PSR has been creep. Unfortunately, there has been a general lack of validated creep data for the thin foils that are the primary component of Solar's PSR. Therefore, a systematic study was undertaken to fully define the operating lines of various thin foils, including SS-347, Inconel 625 and Haynes 230.

The optimized recuperated gas turbine cycle defined in Task 6 for development and commercialization by Solar in ATS Phases III and IV was based on the continuing use of Type 347 stainless steel. This reduces risk due to Solar's extensive and successful experience with this material in PSRs. Given an engine overall pressure ratio, this material selection sets both the design point exhaust temperature via firing temperature (TRIT) and the temperature schedule to which the gas turbine will be controlled during off-design (part load) operation. Development of a PSR material with greater temperature capability will provide two future improvements to Solar's ATS:

- With the advent of turbine airfoil material and cooling technologies that will allow design point firing temperature (TRIT) to be increased, cycle efficiency can be thus improved without the need to increase overall pressure ratio to maintain the present recuperator inlet gas temperature.
- At any given design point temperature, higher off-design (part load) temperatures can be scheduled in order to provide improved part load overall efficiency. This will improve the competitive position of the ATS against natural gas-fueled piston engines which can demonstrate a very flat part load efficiency curve. The variable area nozzle (VAN) in the ATS power turbine is the enabling feature for this plan.

The recuperator materials program includes evaluating several potential recuperator materials for higher temperature and higher pressure operation. These tests include tensile, oxidation and creep tests. All of the tensile tests have been completed, the oxidation tests are in progress and short-term creep tests of the materials will begin shortly. The tensile data are currently being evaluated. Upon completion of these tests a down-selection of materials will occur. A list of the materials under current evaluation are shown in Table 10.

Table 10. Recuperator Alloy Candidates

Material Class	Material
Iron/Chromium/Nickel alloys	347 Stainless steel
	RA 85H
Iron/Cobalt based	N-155
Nickel/Chromium and Nickel/Chromium/Iron alloys	Inconel 600
	Incoloy 800
	Incoloy 825
Nickel/Chromium/Molybdenum	Inconel 625
	Hastelloy-X
Nickel/Chromium/Tungsten/Molybdenum	Haynes 230
	RA-933

Use of materials with the highest temperature capability – such as Haynes 230 or Inconel 625 – will add significantly to the cost of the recuperator. Typically the cost of these materials is as high as four times the cost of the currently used Type 347 stainless steel. Manufacturing cost thus dictates that these materials be used only in that portion of the recuperator that is actually exposed to high temperature and continuing with Type 347 where the temperature has been reduced by the extraction of heat from the exhaust gas. This concept is being explored in the dual-alloy portion of Subtask 8.7.

This portion of the project has begun by initiating a contract with subcontractor Belt Technologies for laser welding of thin foils of differing alloys. Belt has produced a sample weld of Inconel 625 to Type 347 that appears to have potential for forming without first being given a final roll operation following the weld. Evaluation of formability and other characteristics of these welds will follow.

Thin foil creep testing continued throughout the period covered by this report. Tables 11 and 12 report all the creep results obtained to date by Solar and subcontractor Westmoreland Mechanical Testing and Research, Inc., respectively.

Table 11. 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	l	1203
#12	Long	SS 347	0.0032	17000	1250	560	i	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 11. 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
41	Long	Haynes 230	.003	20000	1300	---	n	n
42	Trans	Haynes 230	0.003	20000	1300	---	n	

g-Ruptured at 2.5% creep.
 h-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 8.5% creep
 n - Test still running
 p - Test stopped at 5% creep
 q - Test stopped at 1% creep

Table 12. 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 ^(d)	(d)
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%

Subtask 8.1 - Low Pressure Drop Recuperator - originally included a flattened tube test that was used to validate analytical calculation of the stress in the PSR sheet that determines its creep life. A flattened tube simulates a scaled up cross section of the recuperator primary sheet profile. This scale up produces a model of sufficient size to attach strain gages.

A room temperature pressure test using this flattened tube showed that measured strains are in good agreement with those calculated from an ANSYS finite element model at pressures below 200 psi - the normal range of operation of ATS recuperators (Figure 19).

Figure 19. Flattened Tubes Tests and FEM Strain Comparison at Room Temperature

Subtask 8.1 has been closed following completion of the recuperator performance portion of this project. The high temperature creep portion of the flattened tube test has been transferred to Subtask 8.7. Creep tests are being conducted on Type 347 stainless steel (3480 hours accumulated to date) and Haynes Alloy 230 (2040 hours accumulated to date). Accumulated creep strain has progressed beyond the saturation point of the strain gages and is now being measured periodically by hand. These tests will be continued to rupture.

8.6 LOW COST CERAMIC MATERIALS

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-AC02-92CE40960 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 13. 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. A search is under way for another supplier capable of supplying a material of this type – a fiber reinforced composite.

Samples of LoTEC's BZP material have been received and will be under test soon.

Table 13. 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

8.9 ADVANCED CERAMIC MATERIALS (Subtask 8.9)

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).

Initially, components considered for development in this material included a turbine interstage duct and a power turbine blade. Applicability of ceramic composite materials in these components was more significant in the ICR gas turbine of Task 3 than in the optimized recuperated power plant identified in Task 6. The final component selected was the transition duct between the combustor can and the stage one turbine annulus in the Task 6 gas turbine. Successful application of a ceramic composite in this component provide the same advantages as the use of ceramic material in combustor cans as described in Subtask 8.8

The statement of work and other purchase order details have been finalized with the subcontractor and a kickoff meeting in July of 1995 set the task in motion.

SECTION 9

SCHEDULE AND BUDGET

9.1 SCHEDULE

Tasks 5, 6, and 7 were completed approximately 8 weeks late to the original Phase II plan. The primary reason was the re-direction of Task 5, 6 and 7 efforts toward providing a quality response to the DOE Phase III and IV SCAP which was issued August 18, 1994. While this date somewhat disrupted the ATS Phase II schedule, Solar considers this to be a very timely release of the SCAP which will contribute significantly to timely completion of Phases III and IV as intended in the year 2000.

The subtasks added to Task 8 by Revision M003 to the contract have recovered from their delayed start and are considered on schedule toward completion by May 30, 1996. This date was set as the close of the period of performance by Revision M004 to the contract.

9.2 BUDGET

As of July 31, 1995, a total of 23,278 labor hours have been charged to the contract versus 25,036 planned. Total program cost (including Solar's cost share) stands at \$3016K versus \$3,693K planned. The current cost underrun is temporary and results from the accumulation of costs by subcontractors and not yet billed to Solar.

An additional 9249 labor hours have been charged to internally-funded development activity in direct support of ATS Phase II. This represents some \$833,000 of cost sharing by Solar in addition to that provided for in the contract.

9.3 FUTURE INVESTIGATIONS

Task 4 - Conversion to Coal - and Task 8.3 - Autothermal Fuel Reformer - are complete and their Topical reports are being prepared for submission early in the next quarter. Work on all remaining Task 8 subtasks will continue as planned.

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 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	<u>National Environmental Policy Act.</u>
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	<u>Pressure Ratio.</u> 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	<u>Particle Rejection Impact Separator.</u> 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	<u>Primary Surface Recuperator.</u> 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 Staggering Combustor.
ZWEIFEL COEFFICIENT	A measure of turbine blade loading based on pitch/chord ratio and gas turning angle as independent variables.