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Advanced Turbine Systems Program Industrial System Concept Development

Author:

S. Gates

Contractor:

Solar Turbines Incorporated
P.O. Box 85376
San Diego, California 92186-5376

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Charles Alsup

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2.6 Advanced Turbine Systems Program Industrial System Concept Development

S. Gates
Solar Turbines Incorporated
P.O. Box 85376
San Diego, CA 92185-5376

Objective

Phase II

The objective of Phase II of the Advanced Turbine Systems Program is to develop conceptual designs of gas fired advanced turbine systems that can be adapted for operation on coal and biomass fuels. The technical, economic, and environmental performance operating on natural gas and in a coal fueled mode is to be assessed. Detailed designs and test work relating to critical components are to be completed and a market study is to be conducted. (Reference 1)

Background Information

Throughout its 35 year history as a supplier of industrial gas turbines, Solar has maintained a careful surveillance of the marketplace into which the company's product is sold. This effort has paid off in the growth of Solar into the world's leading supplier of mid-sized industrial gas turbine systems.

Based on this ongoing evaluation of the marketplace, Solar established short- and long-term product development goals which coincide exactly with ATS goals as set by the DOE in four areas:

- Reduced exhaust emissions.
- Increased Reliability, Availability, Maintainability, Durability (RAMD).
- Reduced cost of power.
- Increased thermal efficiency.

Entering into Phase II of the ATS Program, Solar has quantified goals in these four areas as shown in Table 1.

Table 1. Advanced Turbine System Goals

Parameter	Solar's ATS
Thermal Efficiency	50%
Exhaust Emissions NO_x	8 ppm
Exhaust Emissions CO and UHC	15 ppm
Cost of Power (COP)	10% Reduction from Today
Reliability, Availability, Maintainability, and Durability (RAMD)	Equal to or Better than Today

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Project Description and Results

Reference 2 identified an intercooled and recuperated (ICR) gas turbine as the power plant best suited for development to meet ATS objectives. The technologies that will need to be incorporated into an ICR to meet these objectives are within the capability of development by a manufacturer of **industrial** gas turbines, i.e., Solar. More importantly, these technologies are likely to find ready acceptance in the **industrial** gas turbine marketplace, i.e., characterized by moderate risk and reasonable cost. Many of these technologies will also find application in Solar's current product line and as retrofit improvements in Solar's 9200-unit installed fleet.

Recuperation of the classic Brayton cycle gas turbine is a well-known efficiency improvement that has been applied at levels of success primarily established by the cost and durability of the required heat exchange device. At any given level of peak temperature a recuperated Brayton cycle will have an optimum overall pressure ratio. At pressure ratios above this optimum, recuperation capability is reduced by the narrowing gap between exhaust temperature and compressor discharge temperature.

The addition of one or more stages of intercooling into the compression process of the Brayton cycle will significantly reduce the work input required by the compression process. The combination of intercooling and recuperation into an ICR cycle produces an increase in both specific power and thermal efficiency. The thermal efficiency improvement derives from an increased temperature differential between the exhaust gas stream and the compressor discharge air. This enables the recovery of a greater portion of the thermal energy in the exhaust gas. In a modern ICR, thermal efficiency continues to increase with pressure ratio and with temperature.

Task 3 of Solar's ATS Phase II program is entitled, "System Selection." (Tasks 1 and 2 fulfilled certain non-technical contractual requirements.) Task 3 optimized the design of an ICR gas turbine cycle as shown in Figure 1 at a pressure ratio of 16:1 and a firing temperature of 2500°F (TRIT). Based on state of the art component performance this cycle will operate at the 50 percent thermal efficiency stated as the ATS goal in Table 1. However, achievement of this level of thermal efficiency also requires the use of ceramic materials in the high pressure turbine stages. The application of cooling technology which is achievable within the ATS planned timeframe results in a reduction of one to two points of thermal efficiency below the 50 percent level.

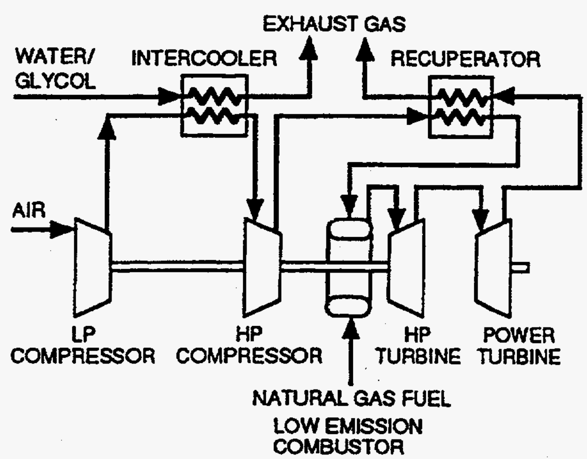


Figure 1. ICR Gas Turbine With Free Power Turbine

This ICR design included the following components:

- Low-Pressure Compressor -- Three to five stage axial compressor with variable guide vanes.

- Intercooler -- Two stages (air to liquid + liquid to air) at 85 percent thermal effectiveness.

- High-Pressure Compressor -- Four to six stage axial compressor with variable guide vanes.

- Recuperator -- Solar's proprietary primary surface recuperator (PSR) at 90 percent thermal effectiveness.

- Combustor -- Can-annular, low emission catalytic system.

- Turbines -- One or two stage (depending on whether a one- or two-spool design is selected) axial gas producer turbine. Two stage free power turbine with a variable area nozzle (VAN) in the first stage.

This arrangement of an ICR gas turbine was carried forward into Task 6 - System Definition and Analysis - for further development. Early in the performance of Task 6 it became apparent that the ICR gas turbine was not the ideal candidate for development and field test in Phases III and IV of the DOE's ATS program. The following factors led to this conclusion:

- The DOE's Solicitation for Cooperative Agreement Proposal (SCAP), Reference 3, 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 timeframe. 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. Fifty 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 and industrial ATS:

  - The industrial gas turbine marketplace can be characterized as "risk-averse." This term describes a reluctance on the part of industrial 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 Task 5 Market Study indicated a strong future demand for an ATS of approximately 5 MWe 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 (> 20 megawatts).

As a consequence of these market- and program-driven considerations, Solar's efforts in Task 6 were redirected toward the definition of an optimized recuperated gas turbine. An optimized recuperated gas turbine is defined as one in which all components and operating parameters of the core gas turbine are optimized in support of the recuperated cycle with no requirement for operation as a simple cycle gas turbine. Most recuperated gas turbines in operation today are based on the addition of a recuperator to an existing simple cycle machine and, as such, fall short of the performance potential of an optimized recuperated cycle.

Recuperated Gas Turbine Arrangement and Characteristics

The recuperated gas turbine (Figure 2) is arranged in a manner similar to the ICR gas turbine of Figure 1. Note that there is now no intercooler shown as part of the compressor. Without the intercooler to maximize recuperation potential by reducing compressor exit temperature, an effective level of recuperation must be sought through careful selection of compressor pressure ratio.

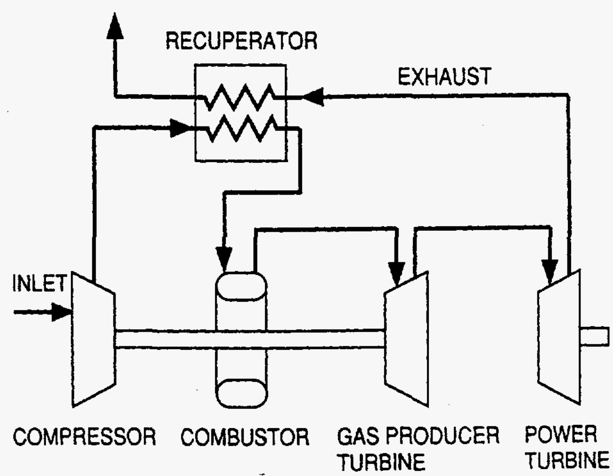


Figure 2. Recuperated Gas Turbine

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 ATS program timeframe occurs between pressure ratios (PR) of 7.5:1 to 8.9:1 and turbine inlet temperatures (TIT) of 1121 to 1238°C (2050 to 2260°F). Solar selected the higher PR because of its increased potential for higher thermal efficiency through the application of future high temperature turbine blade and recuperator materials 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 2. 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.

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

Compressor Description

The ATS compressor (Figure 3) will be scaled directly from several stages of the proprietary 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 utilizes controlled diffusion airfoils in 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).

Recuperator Description

The ATS Primary Surface Recuperator (PSR) is a compact design that provides high effectiveness, moderate pressure drop, and long life (Table 3). 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 4 and 5), the basic building block of the PSR. Each air cell is pressure checked before it is welded into the recuperator core assembly (Figure 6). There are no internal welds or joints within the air cell, and the lack of welds between cells renders the assembly free from the effects of thermal expansion and contraction that plague other recuperator designs.

The PSR has been extensively analyzed using a model which are described later in the

Table 2. 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% Wa*	347 SS Recuperator
Metallic/Ceramic	1185 (2166)	8.92:1	45%	9.7% Wa*	347 SS Recuperator

* Engine inlet airflow.

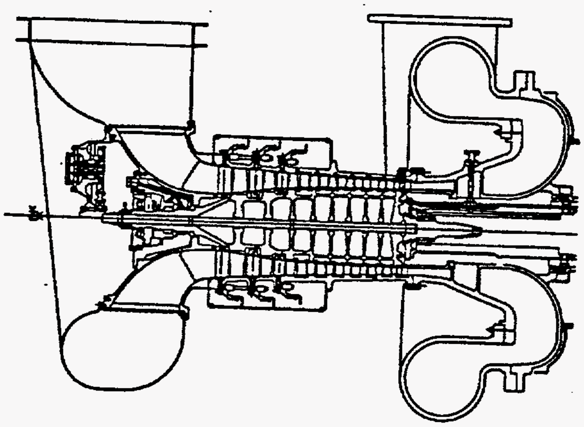


Figure 3. ATS Compressor

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 7.0 percent. 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.

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 shell-and-tube, brazed plate-fin, and PSRs. During the 1970s, Solar industrial gas turbines were delivered to customers with shell-and-tube 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.

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

Table 3. 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.				

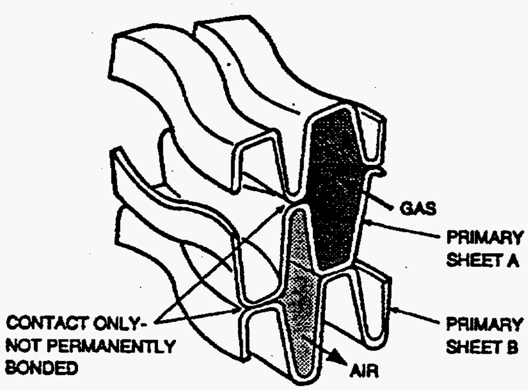


Figure 4. Primary Surface Sheets

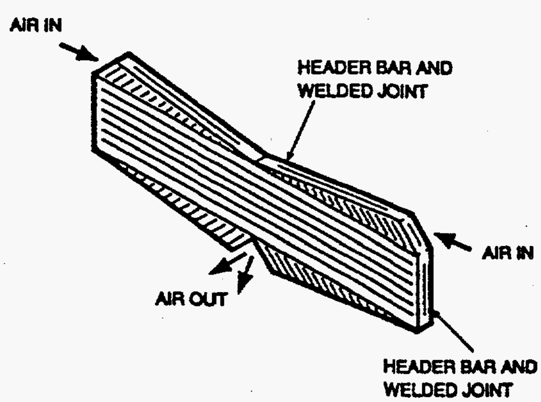


Figure 5. PSR Air Cell

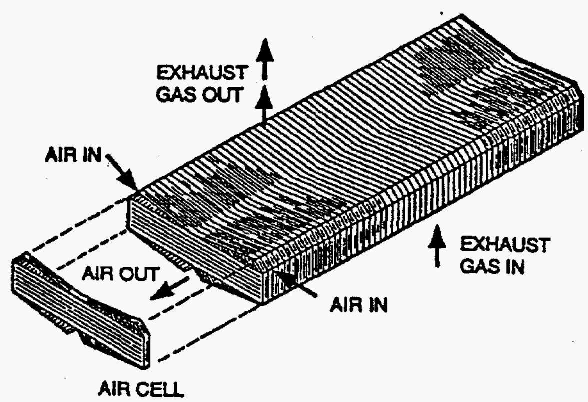


Figure 6. PSR Core Assemblies

Combustor Description

The selection of a combustion technology for ATS was influenced strongly by the goals of reducing NO_x emissions to 8 ppmv initially and 5 ppmv ultimately. Solar has selected catalytic combustion and ultra-lean premixed combustion (ULP) as the technologies with the highest probability of achieving these goals within a timeframe consistent with the program schedule.

Laboratory testing of catalytic reactors has demonstrated NO_x levels consistently below 5 ppm. Internally funded and ATS Phase II, Tasks 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 advancements in the areas of premixing, variable geometry controls, and advanced combustor cooling will allow ultra-lean premixed operation at NO_x levels down to 8 ppmv. Solar's combustor design will accommodate either combustion technology with a minimum of redesign.

As a backup to the catalytic combustor (Figure 7) development, a 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 III. In the event catalytic combustion is not deemed ready for the demonstrator, catalyst development can continue and the technology will be retrofitted into existing engine designs.

The ULP combustion system (Figure 8) will build upon Solar's lean premixed combustion technology (SoLoNOx™) that was recently introduced to the gas turbine market (Figure 9). Lower NO_x 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 NO_x sources in gas turbine combustors.

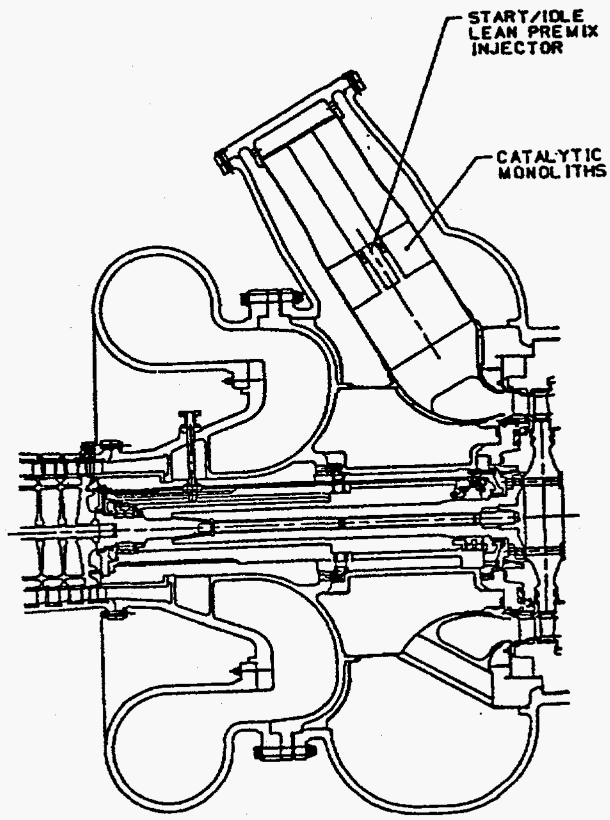


Figure 7. Engine Cross-Section Showing Can-Annular Catalytic Combustor

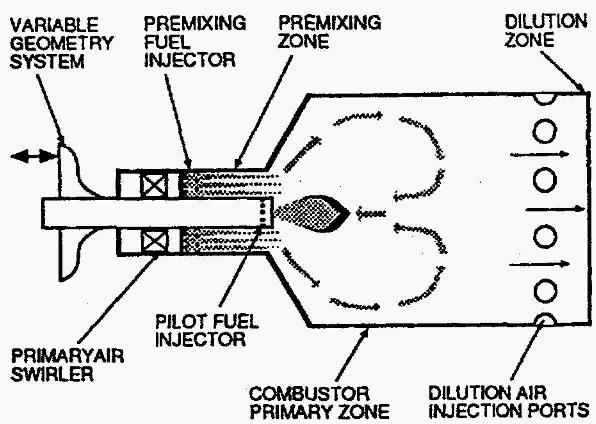
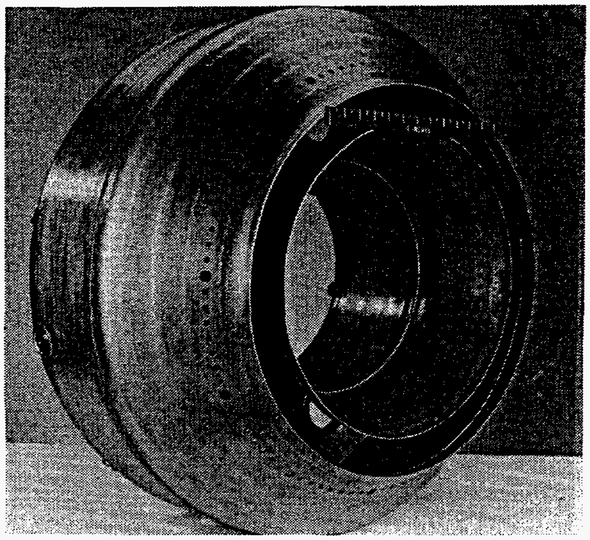


Figure 8. ATS Ultra Lean Premixed Combustor Approach



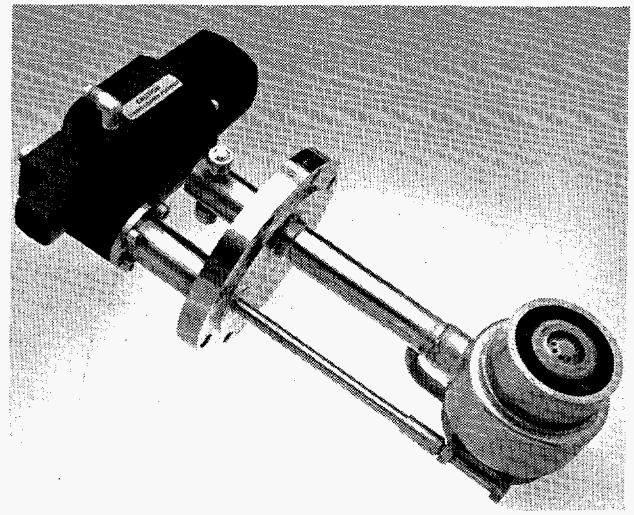


Figure 9. SoLoNOx Combustor Liner (left) and Fuel Injector (right)

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 design employs conventional high temperature sheet metal construction; advanced cooling techniques beyond traditional film cooling are employed to maintain acceptable liner wall temperatures. As a result, 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 Ceramic Stationary Gas Turbine (CSGT) program will guide the application of ceramics in the ATS combustion system.

Turbine Description

The design of all turbine stages is optimized for aerodynamic performance while maintaining mechanical integrity over the required life. The performance of the turbine stages - one gas producer stage and three power turbine stages - is based on Solar's "ACE" aerodynamic technology program mentioned earlier.

Turbine Cooling and Material Selection

Any Brayton Cycle efficiency gain to be realized with increase in peak (firing) temperature is very dependent upon the energy expended in cooling the turbine materials to the temperature level required for commercially practicable life. Normally this energy expenditure takes the form of air flow bled from the compressor which then bypasses the combustion process and varying portions of the expansion process. This is true of all Brayton Cycle forms, simple or complex.

In complex cycles there are additional opportunities for improving cooling effectiveness. In a recuperated cycle, for example, air to be returned early in the expansion process can be bled from the recuperator exit rather than the compressor exit. While this may increase the actual cooling air bleed flow, it can improve thermal efficiency by using this flow to recover additional exhaust energy for use in the expansion process. Where cooling air temperature is of critical importance, any intercooled cycle has a lower compressor discharge temperature and bleed air can be further cooled by a second pass through a dedicated section of the intercooler.

Given a firing temperature selected on the basis of cycle optimization or other consideration, cooling air requirement becomes the key variable in determining thermal efficiency. This effect is shown for Solar's optimized recuperated gas turbine in Figure 10. At 2125°F, present cooling technology requires some 20 to 22 percent of the gas turbine's inlet air flow to be bled for cooling.

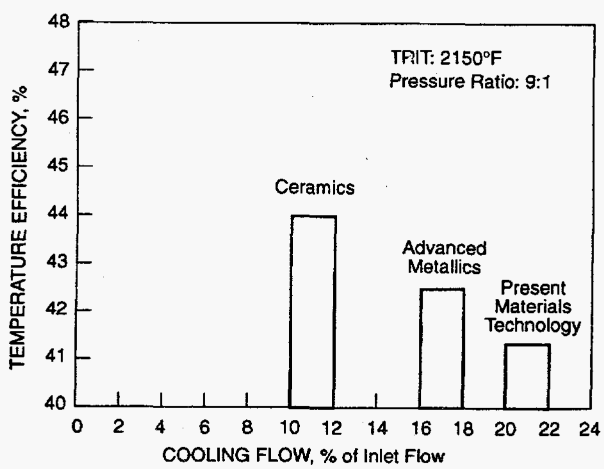


Figure 10. Thermal Efficiency of Solar's Recuperated ATS Gas Turbine as a Function of Cooling Air Flow

Metallic blade cooling technology which can be developed in an ATS program will reduce cooling air bleed sufficiently to provide a one point improvement in thermal efficiency. An additional two points can be derived from a commercially practicable introduction of ceramic blades.

System Definition

The proposed layout for the recuperated cycle ATS design is shown in Figure 11. 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 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.

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. With two sizes in mind, 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 aerodynamic components:

- For constant rotor linear tip speeds, geometrically similar components will operate with:
  - Identical pressure ratios.
  - Identical efficiencies.

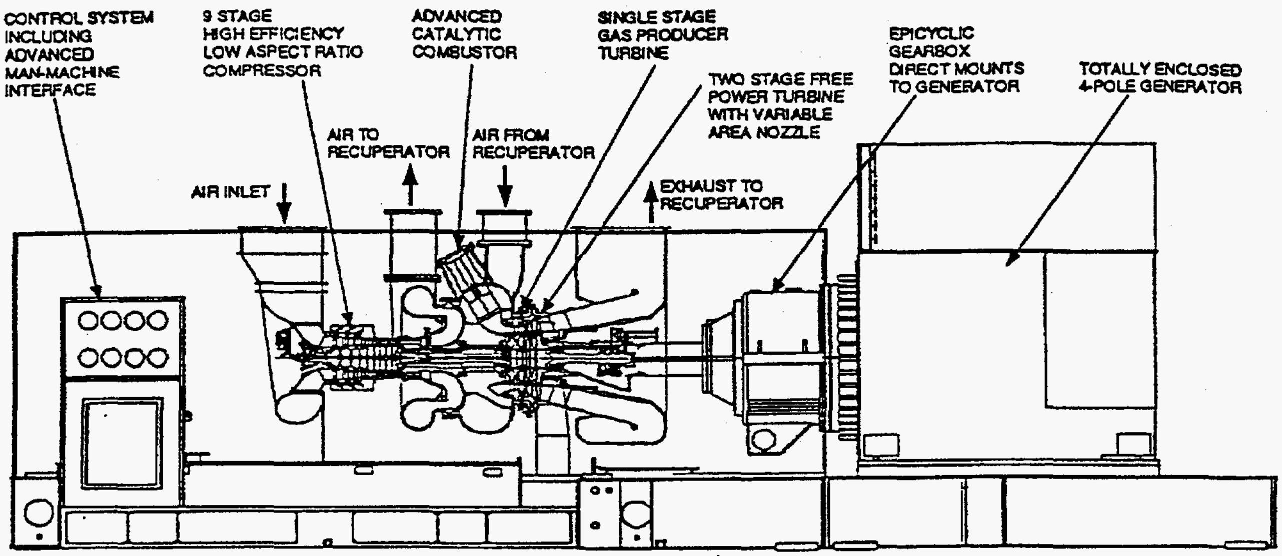


Figure 11. Solar's Advanced Turbine System (Cross-Section)

- 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 leading and trailing edge thickness, end wall clearances, and surface finishes.

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 16:1 PR and 1340°C (2450°F) TIT optimized ICR. This approach allows continued usage of the well-proven Type 347 stainless steel as the recuperator sheet material.

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.

Solar's ATS Phases III and IV Program Plan (Task 7)

Solar has been awarded a cooperative agreement for ATS Phases III and IV based on our response to the DOE's SCAP (Reference 3). As a part of this proposal, Solar has prepared a Research, Development, and Test Plan that builds upon ongoing ATS Phase II 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 selected 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 U.S. 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 accordance 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.

Market Study (Task 5)

In the performance of Task 5 of ATS Phase II, Solar called upon extensive internal knowledge of the gas turbine marketplace which has installed over 9000 Solar gas turbine packages to date. In addition, two outside agencies were subcontracted to provide Solar with an independent view of future opportunities for gas turbine power in general and ATS power in particular.

- 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.
- 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.
- 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 NO_x) 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.

- 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.

- 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. Because 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). Low cost duct firing greatly contributes to flexibility in meeting demands of such users with highly cyclic or seasonal process heat requirements.

A market segment that has recently emerged with a potential for the ATS-size power system, and which Solar has recently entered, is high-speed light 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.

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 ATS defined in Task 6. Thus, as has been the case in over three decades of Solar experience in the gas turbine marketplace, Solar's ATS design has been shaped by user requirements.

Based on the characteristics of the ATS defined in Task 6 and volumes forecast by the Market Study of Task 5, the following view of the year 2020 was formulated:

- 26,880 MWe (36 million shaft 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 NO_x 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.

Development of Critical Technologies (Task 8)

The DOE has recognized that, if new technologies are to be incorporated into an ATS in a timely manner, an early start on their development is good insurance. Accordingly, such technology development has been written into Phase II contracts. This element of Solar's Phase II contract - Task 8, titled "Design and Test of Critical Components." Task 8 includes materials development in support of the ATS recuperator and turbine disks, advanced ceramic materials development, low emissions combustion research, and advanced control technology.

Materials Development - Recuperator

The temperature capability of the recuperator sheet material - presently Type 347 stainless steel - limits attainable thermal efficiency at all levels of pressure ratio. This limiting exhaust temperature is approximately 1230°F for Type 347 stainless steel. A low-cost alternative being examined in Task 8 is one or more of the high temperature ultrafine precipitate strengthened (HT-UPS) austenitic stainless steel alloys under development at Oak Ridge National Laboratory.

Large increments of temperature capability can be obtained through the use of nickel-base alloys such as Inconel 625 or Haynes 230. Cost of these alloys approaches four times the per-pound cost of Type 347 stainless steel. Task 8 will determine the prospects for using such alloys only in regions where temperature will be above the limit for Type 347, thus minimizing cost. Methods of joining the two alloys will be examined along with the formability and other critical characteristics of the joined pair.

Using a laser welding technique developed by a subcontractor, successful joining of 347 stainless steel to Inconel 625 alloy has been accomplished. The resulting joint is sufficiently free of any sort of raised bead so that samples are being sent directly to Solar's recuperator sheet forming process for formability trials. It does not appear at this point that any sort of final roll process will need to be introduced following the weld operation.

Materials Development - Turbine Disks

The current material of choice for turbine disks is a forged high temperature - usually nickel based - alloy. This material is chosen for its high low-cycle fatigue strength required for survival of the large strain excursions involved in gas turbine start-run-stop cycles. Near the rim at the point of blade attachment, these materials lack the creep resistance of cast versions of the same or a similar alloy. Adequate creep life of this region of the disk is maintained by cooling with compressor bleed air, at the cost of cycle efficiency. Increasing cycle firing temperature requires more cooling air. Flattening of combustor outlet temperature profiles as required to maintain low stress levels in ceramic airfoil at a constant average temperature will also raise disk rim temperature and require additional cooling.

Task 8 efforts are developing a method of producing a strong bond between a turbine rim section cast of creep-resistant high temperature alloys and a center section which maintains the low cycle fatigue properties of the present materials. Once the right alloy pair and bonding process is identified, its characteristics will be defined to the gas turbine designer for application to Solar's ATS as well as for introduction to the balance of Solar's product line.

Mar-M-247®, the material chosen for the high-temperature (rim) portion of the dual-alloy disc has been successfully spray-cast into rings suitable for bonding with the central portion of the disc. Coupons of Mar-M-247 have been HIP-bonded to coupons of Udimet® 720 hub alloy and the resulting joint is undergoing metallurgical evaluation.

The spray-cast process provided by subcontractor Howmet offers additional possibilities for application to Solar's non-ATS product line. These include parts which cost less than those made from forged rings, and parts requiring creep-rupture properties not obtainable in forged alloys.

Materials Development - Ceramics

Going beyond the wealth of ceramic technology that will flow into the ATS from Solar's Ceramic Stationary Gas Turbine

(CSGT) Program with the DOE, Task 8 will focus in two specific areas:

- Candidate ceramics for use in association with the catalytic combustor and its associated ducting will be identified. In ATS machines, these materials will serve to free cooling air applied to metallic ducts for use in emissions reduction.

- A second focus will be on developing the manufacturing process and accurately determining the life characteristics of parts made from ceramic composites. The combustor can-to-turbine nozzle transition duct in the ATS gas turbine is the candidate part selected for this evaluation with subcontractor B.F. Goodrich Supertemp and based on a SiC/SiC material.

Component Development - Combustion

As a part of Task 8, Solar is evaluating a subscale ATS combustor in an existing high pressure test rig (Figure 12). The objective of this test is to determine performance of the catalyst bed and the fuel-air premixer under ATS conditions. This program will next progress to a full-scale single can of the multi-can annular catalytic combustor intended for the ATS. Working with a subcontractor supplying the catalyst in a ceramic matrix, Solar is developing the combustor to meet the ATS requirement of 8 ppmv of NO_x and 15 ppmv of CO and UHC.

Once key characteristics of the catalytic reactor in the subscale rig have been determined, these will be applied in a full scale rig now being designed. This rig will model the entire catalytic combustion system on the basis of one can sized for the ATS gas

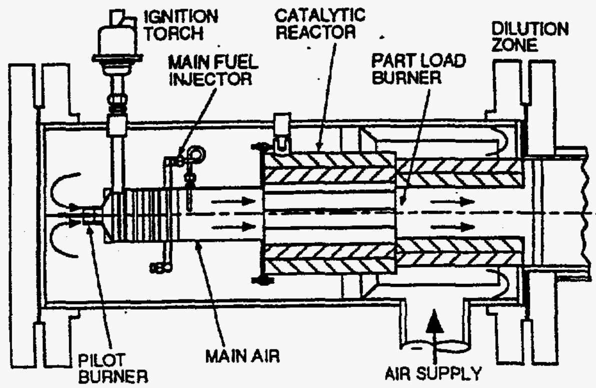


Figure 12. Subscale Catalytic Combustor Rig

turbine. This system will consist of the catalytic reactor developed in the subscale rig together with associated elements such as the fuel-air mixer and the post-catalyst combustion region.

To date, the sub-scale rig has been operated under stable conditions with NO_x emissions below 5 ppmv. The subscale rig has also produced valuable information on the design of a fuel-air premixer that will deliver evenly distributed fuel concentrations to the inlet face of the reactor. The design of the full-scale rig is being completed with a post-catalyst combustion region sized using NASA-derived chemical kinetics software to provide complete CO burnout.

Component Development - Recuperator

In addition to the recuperator material task previously discussed, a second task deals with recuperator thermal and flow performance required in support of ATS cycle performance goals. The geometric parameters of the primary heat transfer surface can be varied in order to provide the combination of heat transfer effectiveness and static pressure loss required by the cycle. In the case of the ATS, the goal is to preserve the 90 percent thermal effectiveness used in prior applications of the primary surface recuperator (PSR) while reducing the static pressure loss in both air and exhaust gas streams.

The design of the new surface was accomplished using codes derived both empirically from previous test work and by application of textbook heat transfer principles. Thermal and flow performance of the ATS recuperator has been validated at the Caterpillar Technical Center, using the apparatus described in Reference 4. Under ATS design point operating conditions, thermal effectiveness was measured at 90.3 percent (versus 90.0 percent required by the ATS cycle) and total (air- and gas-side) static pressure loss at 6.8 percent (versus a maximum of 7.0 percent) allowed by the ATS cycle.

Component Development - Autothermal Fuel Reformer (ATR)

Work on the ATR under Solar's ATS Phase II contract as described in Reference 4 has been completed. Concentrations of 70 percent free hydrogen in the secondary fuel reformed from natural gas were achieved. Reformation of liquid fuel (Diesel No. 2) produced 60 percent free hydrogen. Satisfactory resistance of the reforming catalyst to poisoning by fuel-borne sulfur was also demonstrated.

The ATS to be developed by Solar during Phase II does not include an ATR; however, Solar considers this process to be a significant contributor toward the clean burning of a wide variety of fuels in future gas turbines including the ATS. Accordingly, ATR development will continue at Solar using internal R&D funding.

Component Development - ATS Control System

In order to fully realize all of the benefits of ATS, program activity has to proceed beyond the boundaries of the gas turbine itself and through the entire **system**. Within the **system** all support subsystems must be optimized for full support of the ATS goals designed into the gas turbine itself.

One such subsystem of critical importance is the control system - not just a gas turbine control but an ATS **system** control. During Phase II, Solar is designing an advanced Man/Machine Interface (MMI) which will apply microprocessor technology so as to provide improved efficiency and RAMD along with reduced cost and emissions. Important features of this system are described below:

- The system will provide easy communication with other system/plant computers and control equipment over industry standard networks. This will allow optimization of the complete system of which the ATS is a part, improving efficiency and reducing emissions.

- Automatic intelligent reduction/analysis of control system data into advisory information. This will assist the operator in the diagnosis of plant operation and to set maintenance schedules which will result in higher levels of RAMD. He will also be able to optimize plant operation for increased efficiency, lower emissions, and lower cost of power.

- Long range communication ability will be improved by utilizing media such as telephone lines, microwave links, and communications satellites. This will allow operation, data collection and analysis and diagnostics and maintenance to be performed on multiple units from a central location. The system will also interface with Solar's Customer Services Center to provide rapid response to problems.

- Modular options, easily integrated at low cost into the customer's MMI will be provided based on the customer's needs. These can include remote starting and operation, interfacing with existing plant and process controls, on-line economic analysis and many others.

- Easy, in-field reconfiguration of the MMI will minimize the cost of future updates that may be required by changing requirements of the system.

Other ATS-Related Technology Development Programs at Solar

Ceramic Stationary Gas Turbine (CSGT)

This DOE-sponsored program with Solar as the prime contractor and eight cost sharing subcontractors is a technology demonstrator program with the retrofit of ceramic components into existing industrial gas turbines as its ultimate goal. Starting with the development of design methodology for these components, this program has produced detailed designs for components to be tested in a Solar Centaur® 50 gas turbine. Component rig and engine tests are under way, preceding final validation of CSGT technology in a 4,000 hour field test. Commercialization of the retrofit design for the Centaur 50 and other gas turbine models will follow successful completion of this field test.

During the current quarter, the Centaur 50 test engine completed two successful two-hour test run (one hour each at temperature) with stage one turbine blades of Norton NT164 material and Allied Signal GN10 material. Blades were mounted in a conventional metal disc using dovetail-shaped attachments.

Materials/Manufacturing Development Programs with ORNL

Solar is involved in a manufacturing program with the Oak Ridge National Laboratory (ORNL) as a subcontractor - along with other gas turbine manufacturers - to prime contractor Howmet. This program, awarded in September, 1994, has as its goal the development of lower cost, high performance single crystal components. Field demonstrations of the resulting components are scheduled in the fourth year of the program, making Solar's ATS field test a candidate host for these tests.

In addition to its key contributions to ATS, both of this program will provide spin-off technologies for inclusion in Solar's current product line as well a for retrofit into Solar's fleet of more than 9200 gas turbine systems sold around the world.

Summary

Solar approached Phase II of the ATS program with the goal of providing a system that would be capable of 50 percent thermal efficiency. An intercooled and recuperated (ICR) gas turbine was identified as the ultimate system to meet this goal in a commercial gas turbine environment. Proceeding with commercial input from detailed market studies and examining the boundaries of the DOE's ATS program as defined in the

Solicitation for Cooperative Agreement (SCAP) for Phases III and IV, Solar redefined the company's proposed ATS to fit both market and sponsor (DOE) requirements. The resulting optimized recuperated gas turbine will be developed in two sizes, 5 MWe and 15 MWe. It will demonstrate a thermal efficiency of approximately 43 percent -- a 23 percent improvement over current gas turbine product in the industrial size range. Other ATS goals -- emissions, RAMD (reliability, availability, maintainability, and durability), and cost of power will be met or exceeded. During FY 1995, advanced development of key materials, combustion and component technologies proceeded to the point of accepting them for inclusion in ATS Phase III development along with parallel path risk-reduction approaches.

Future Work

The DOE has awarded Solar the Cooperative Agreement for performance of Phases III and IV of the ATS Program as a result of Solar's proposal based on Phase II technical and commercial studies. In anticipation of this award, Solar has begun work on the final design of the ATS and was proceeding rapidly on this project at the time of the award. Fiscal 1996 will see the completion of Phase II technology work as well as the addition of the Phase III efforts to these and associated projects. Technology projects and the basic ATS product design project will lead to an 8000-hour field evaluation test of both ATS sizes (5 MWe and 15 MWe) beginning early in CY 1998 and commercial availability of the Solar/DOE ATS in the year 2000. This progress will be supported by concurrent DOE programs at Solar such as the ceramic retrofit (CSGT) program.

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