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# Advanced Turbine Systems Program - Conceptual Design and Product Development

## Final Report
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For
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# Section 1

## EXECUTIVE SUMMARY

Definition of a family of Advanced Turbine Systems (ATS) is the principal task covered in this report. The ATS concept proposed will exceed the four goals set by DOE; 15% improvement in thermal efficiency over current gas turbine systems; less than 10 ppmv NOx and less than 15 ppmv of CO and UHC; cost of electricity will be 10% less than current systems; and reliability, availability, maintainability, and durability (RAMD) will be better than current systems. A conceptual design was used to make a market survey, and led to identification of two major markets. These were: Solar's traditional market as a supplier of gas turbine systems to the oil and gas industry; and a new market based on the concept of distributed electric power generation.

The oil and gas industry will continue to move off-shore such that there will be shipments of nearly 2 million H.P. (1300 MW) to domestic customers and nearly 11 million H.P. (8000 MW) to foreign customers in the period 2000 to 2010. The electric power shipments will reach 8000 MW to domestic and nearly 5000 MW to foreign users in the same period. Total shipments to all customers will be 22,000 MW.

Market input continued as more detailed cycle analysis and design was begun. Eventually, an optimized recuperated engine cycle was selected. This cycle will achieve the efficiency goals at a lower pressure ratio and lower firing temperature than a simple cycle machine. It will be more readily accepted in the marketplace than a simple cycle machine fired at 2450-2600°F. The ACE compressor has been under development using Solar funds and allowed selection of nine stages to provide a pressure ratio of 8.92 at an adiabatic efficiency of 88.5%. This was found to provide an ATS with 45% efficiency at a TIT of 2166°F for a 32% increase in efficiency over the current level of 34%. Such a machine will be introduced to the market by the year 2000 to be followed later by the intercooled recuperated (ICR) with 50% efficiency (47% increase over currently available machines).

Nine technologies were identified as critical to the success of ATS, either as alternate, back-up technologies or essential to successful market introduction. Work on these technologies is included in this Final Technical Report.

# Section 2

# INTRODUCTION

This Final Technical Report presents the accomplishments on Contract DE-AC21-93MC30246 in the period August 30, 1993 to March 31, 1996 on Phase II of the Advanced Turbine Systems (ATS). The ATS is an advanced, natural gas fired gas turbine system that will represent a major advance on currently available industrial gas turbines in the size range of 1-20 MW.

The activities included four major studies to define the ATS to be demonstrated in Phase III together with nine studies on critical technology/components deemed essential to the program. The critical technologies included some that were essential to the ultimate realization of the program goals and some that were back-up technologies to ensure overall success.

This Final Technical Report covers a market-driven development. The Market Survey reported in Section 5 identified the customer's performance needs. This market survey used analyses performed by Solar Turbine Incorporated backed up by the analyses done by two consultants, Research Decision Consultants (RDC) and Onsite Energy Corporation (Onsite). This back-up was important because it is the belief of all parties that growth of the ATS will depend both on continued participation in Solar's traditional oil and gas market but to a major extent on a new market. This new market is distributed electrical power generation. Difficult decisions have had to be made to meet the different demands of the two markets. Available resources, reasonable development schedules, avoidance of schedule or technology failures, probable acceptance by the marketplace, plus product cost, performance and environmental friendliness are a few of the complex factors influencing the selection of the Gas Fired Advanced Turbine System described in Section 3. Section 4 entitled "Conversion to Coal" was a task which addresses the possibility of a future interruption to an economic supply of natural gas.

System definition and analysis is covered in Section 6. Two major objectives were met by this work. The first was identification of those critical technologies that can support overall attainment of the program goals. Separate technology or component programs were begun to identify and parameterize these technologies and are described in Section 7. The second objective was to prepare parametric analyses to assess performance sensitivity to operating variables and to select design approaches to meet the overall program goals. In general, these goals can be met by more than one approach and final decisions were often made on the need for market introduction by the year 2000 plus the perceived readiness for market acceptance. The year 2000 ATS could then be followed by uprated versions based on the ATS technologies.

All ATS models to be introduced will meet program goals. These goals are:

- Thermal efficiency 15% greater than current gas turbine systems
- Emissions less than 10 ppmv of NOx and less than 15 ppmv of CO and UHC
- Cost of power to be 10% less than current systems.
- Reliability, availability, maintainability and durability (RAMD) equal to or better than current systems.

Market-dominated issues such as efficiency at part load, life cycle costs, siting requirements and many other customer-influenced factors were extremely important. Consideration of many of these led to an early decision that the intercooled recuperated (ICR) engine was not the preferred machine for the first ATS model to be delivered in the year 2000. A recuperated cycle was chosen after many iterations for this ATS. As noted earlier, this model will exceed all the goals on the program. In addition, the lower TRIT and lower pressure ratio of the recuperated versus the ICR engines will provide a better RAMD to the customer. It is believed that the ICR model will be introduced soon after the recuperated version achieves market acceptance.

Beyond the year 2000 model, advanced technologies, materials, and/or components will be introduced subsequently in a market-acceptable progression. The technical work to support these introductions has been started in Phase II and is reported here. Work will continue in Phase III with the intent of readying these technologies for introduction by the year 2000. These technologies are:

- Performance validation of the low pressure drop, primary surface recuperator (PSR)
- Catalytic combustor technology
- Autothermal fuel reformation
- Dual material, high temperature turbine disk
- Full scale catalytic combustor
- Total plant controls
- High temperature materials for PSR
- Low cost ceramic materials for low pollution combustors
- Advanced ceramic materials for complex combustor duct shapes

These critical technologies must be developed to realize the overall efficiency goal vs. the current industry standards of 34% efficiency for simple cycle industrial gas turbines in the ATS size class. Progress in each of these technologies is reported in various sub-sections of Section 7.

# Section 3

# SELECTION OF CYCLE TO MEET MARKET NEEDS

This work constituted WBS 2.3 on the ATS program. Topical Report 3 should be consulted for more details of this work.

## 3.1 WBS 2.3 - SELECTION OF GAS FIRED ADVANCED TURBINE SYSTEM (GFATS)

This task was one of the first to be completed and met two needs. One was a selection of a GFATS for use in the market survey. The second was provision of guidance for individual technologies that were deemed essential to ultimate success. Work on these critical technologies is reported separately in this Report. The GFATS work was completed in April 1994 and Topical Report No. 3 was issued in July 1994. One result of this early completion is that as market input (Section 5) and design input (Section 6) became available, significant changes occurred. These changes are identified in the appropriate sections.

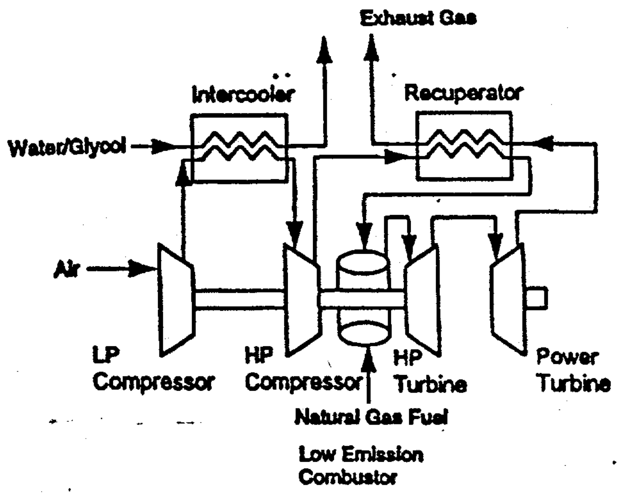
This task identified an intercooled and recuperated (ICR) gas turbine as the eventual Solar product to result from Solar's internal New Product Introduction (NPI) program combined with D.O.E.'s ATS program. When fired in the region of 2500°F at the optimized pressure ratio, this machine will be capable of operating at 50 percent thermal efficiency (turbine shaft power/fuel LHV). Activity in this task 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.

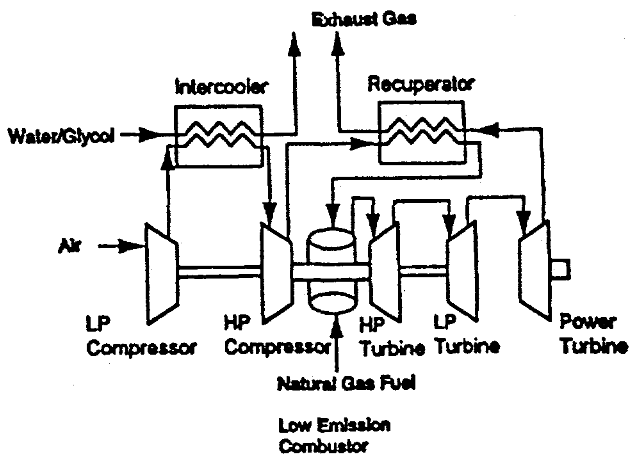
The issue of a one-spool versus a two-spool gas producer section remained open at the conclusion of this study in April 1994.

## 3.2 GENERAL CONFIGURATION

The ICR gas turbine system chosen in Phase I can be configured in various ways. The first configuration examined was an intercooled, one-spool gas turbine with a free power turbine (Figure 1). Such an arrangement is particularly attractive for base-load systems when first cost, as a function of the overall life-cycle cost, is very important. A second approach is to use two spools with a free power turbine and to intercool between the two spools (Figure 2). The latter approach provides high efficiency over a wider range of off-design operating conditions than the one-spool configuration. In addition to these two configurations, which were selected as baselines, three other configurations were evaluated. These three were variations of the two-spool baseline configuration, intended to maximize the energy extraction in the first-stage turbine.

All of these approaches were investigated in terms of their ability to meet the ATS50 program goals and also Solar's extended goals (Table 1). The performance of these five configurations was evaluated at both on-design and off-design conditions. The on-design ambient conditions adopted for the analyses were those associated with a sea-level, 59°F day as defined by the International Standards Organization (ISO). Hot day conditions were defined as 100°F, again at sea level. An existing computer code that provided a simplified analytical method was used initially to determine the relative merits of the two general approaches. This analytical methodology involved the use of a generalized compressor map and operating line to determine potential compressor surge problems.




**Figures 1 (Left) and 2 (Right) Show One-Spool and Two-Spool Gas Producers With Free Turbine**

**Table 1. Advanced Turbine System Goals**

| Parameter | Baseline ATS50 (Year 2000) | Expanded Goals (Year 2005+) |
|---|---|---|
| Thermal efficiency | 50% | 60% |
| Exhaust Emissions NOx | Eight (8) parts per million | Five (5) parts per million |
| Exhaust Emissions CO & UHC | Fifteen (15) parts per million | Twelve (12) parts per million |
| Cost of Power (COP) | 10% Reduction From Today | 10% Reduction From Today |
| Reliability, Availability, Maintainability & Durability (RAMD) | Equal To or Better Than Today | Equal To or Better Than Today |

While the above analyses were being performed, a more sophisticated performance code was under development. This Solar-developed code incorporates both compressor and turbine maps with a cooling model for the turbine section. The cooling model is considered to be extremely important because the air flow required for cooling purposes will largely determine the overall thermal efficiency. This cooling model determines the approximate air flow for turbine blades and vanes given the hot and cold gas temperatures and the materials of construction together with the desired life at a predetermined stress level. The size and shape of the blades and vanes also affects the air flow requirements. These were approximated for the performance analyses based on a combination of theory and past experience. Blade sizes were determined at one set of conditions and then scaled as a function of the chosen cycle pressure ratio (i.e., higher pressures, smaller blades). The stress rupture life initially selected for the blades was fixed in the model at 60,000 hours. In addition, the blades were assumed to be fabricated from directionally solidified materials such as DS CM247LC. These material assumptions also affect the cooling air flow levels through stress- or oxidation-imposed temperature limits. The nozzle guide vanes and ducting were assumed to be fabricated from ceramic materials and were either not cooled or, in the case of the vanes, were minimally cooled.

A more advanced cooling model was also developed, using Solar funds, to replace that initially used. This model invoked more sophisticated cooling concepts and techniques that allowed the cooling air requirements to be reduced. Single-crystal (CMSX-4) blades coated with thermal barrier materials (TBCs) were assumed for the model. As above, the vanes and ducting were assumed to be manufactured from ceramic materials. Variable life and in particular reduced life for blade design (one overhaul cycle [30,000 hours]) was also included in the analysis. A trade-off between reduced life for the turbine section and the resulting increased maintenance costs, can be considered with the ATS50 because its high thermal efficiency provides significantly reduced fuel costs over the life of the system. However, the frequency of engine change-outs and associated downtime must be taken into account. Such considerations represent a continuing market study and are considered in Topical Reports No. 5 and No. 6.

## 3.3 MARKET CONSIDERATIONS

Interplay between market requirements and the optimum configuration for GFATS was a continually re-occurring factor in this work. It was made more difficult by the contrasting needs of the two principal markets identified in the market survey as pointed out by our consultants, RDC, as well as by the yet-to-evolve distributed power market created, to a major extent, by the deregulation of utilities. Another difference was that Solar's traditional market, oil and gas transmission cannot rely on a supply of water whereas distributed power does not appear to have this limitation. These remarks explain why the initial size chosen for the ATS analyses was a 12-MWe or 16,000-hp engine. This size fits well with the commercial industrial power generation marketplace. Further study as to the appropriate size for the dispersed power marketplace is continuing.

A total of five candidate configurations of an ICR were evaluated for their potential to meet the ATS50 goals. The enhanced goals were addressed by adding reheat, ultra-low cooling requirement turbine blades, and chemical recuperation in the form of autothermal reforming to the near-term configuration. Steam cooling of the turbine blades will be considered in site-specific market studies. However, the availability and cost of water may prohibit its use in some locations.

Advantages associated with the one-spool approach (Figure 1) include the ease with which 50 percent or greater thermal efficiency at the design point conditions can be achieved. In addition, the simplicity of the one-spool approach translates to low first-cost and potentially low maintenance costs. The ease with which the single-spool ICR can be started is an issue and must be further evaluated. Although the task of achieving an efficiency greater than 50 percent was judged to be more difficult with the two-spool gas producer section (Figure 2), this approach offers considerably better part-load efficiencies. Such part-load efficiencies are particularly important in load-following applications, and will be investigated further.

Because of the market implications of the differing efficiencies for the one- and two-spool approaches, Solar intends to continue to investigate both configurations. The continuing market study (see Topical Report No. 5) will allow Solar to make a selection that will maximize the commercial applications of the ATS. Both the one-spool and two-spool engines have the same pressure ratio and turbine rotor inlet temperature and thus will have some common components. These common components allow the pursuit of two different configurations with minimal additional effort.

### 3.4 TECHNOLOGY OPTIONS/RISK FACTORS

The technology options in five major areas within the ICR system were evaluated. These areas include:

1) Combustion System
2) Gas Producer Turbine Blades
3) Gas Producer Turbine Nozzle.
4) Recuperator
5) Intercooled Compressor System

The risk associated with the application of the Primary Technology Choice, the Back-up Technologies and the High-payoff Technologies varies within each area (see Table 2). Risk refers to the potential inability to reach one or more of the goals described above, if the component or process in question fails to meet its performance criteria. Generally, however, the Back-up Technologies diminish the risk and the High Pay-off Technologies increase the risk when compared with the Primary Technical Choices.

**Table 2. Component Technology Selection Options**

| System/Component | Primary Technical Choice | Back-up Technologies* | | High Pay-off Technologies** | |
|---|---|---|---|---|---|
| | | First | Second | First | Second |
| Combustion | Catalytic | Ultra Lean Premixed | | Autothermal Reformation | |
| Gas Producer Turbine Blades | Film-cooled Leading Edge | All Film Cooled | | Advanced Uncooled Ceramics | Cooled Metal w/TBCs |
| Gas Producer Turbine Nozzles | Uncooled Ceramic w/TBC | Cooled Metal w/TBCs | Cooled Ceramic | | |

* Descending Technical Risk
** Ascending Technical Risk

Risk will be managed in the ATS50 by evaluating, testing and introducing products to the marketplace with incremental technical advancements. As noted in the Market Survey (Topical Report No. 5), incremental introduction of new technologies may speed market acceptance so that earlier introduction is achieved and field experience is gained.

The completion of development of the high pay-off technologies will probably not all come together until after the contractual demonstration system has been delivered. Therefore, Solar's ATS program demonstration system is likely to consist of choices identified in Table 3 with the back-up technologies from Figure 2 available to ensure timely introduction of ATS.

**Table 3. Solar ATS Demonstrator Technologies**

| System/Component | Selection |
|---|---|
| Combustion | Catalytic |
| GP Turbine Blades | Advanced Single Crystal with TBC |
| GP Turbine Nozzles | Advanced Superalloy (1st) / Uncooled Ceramic Stages (2nd) |
| Primary Surface Recuperator Core Material | Type 347SS |
| Intercooler | 2 Circuit with Water Tower |

## 3.5 ICR CONFIGURATIONS EVALUATED

A one-spool ICR with a free power turbine, and a two-spool arrangement, also with a free power turbine, were the two primary configurations evaluated (Figs. 1 and 2). In both of these configurations the air flow required for cooling the turbine section plays a dominant role in determining the overall efficiency. In general, the lower the turbine cooling air flow, the higher the cycle efficiency. Because of this need to minimize the turbine section cooling air flows, the ideal configuration would have the smallest possible number of turbine stages, and the greatest temperature drop on the first turbine stage. A large temperature drop over the first-stage turbine translates to lower operating temperatures for the later turbine stages and thus a lower total cooling flow requirement. In order to increase the temperature drop over the first-stage turbine, the level of work extracted has to be increased.

In the two-spool system (Fig. 2) each of the two separate compressors is driven by a dedicated turbine section. Each of these turbine sections has a minimum of one row or stage. Two stages may be used in order to maintain the desired high turbine efficiencies. With the work split among four turbine stages the temperature drop over any one stage is low. This observation led to a number of variants of the two-spool configuration, all of which were intended to maximize the work extraction in the first turbine stage. The variant that initially appeared to present the greatest potential for increased work extraction was one in which the power turbine was positioned as the first turbine stage rather than the HP compressor turbine as shown in Figure 2 (see Topical Report No. 4 for details). However, it was found that the poor speed match between the second turbine section and the high-pressure compressor would force the use of a gearbox between the two sections. Variable nozzle guide vanes would also be needed in front of both the power turbine and the second gas producer turbine stages.

Use of a single turbine stage to drive the HP compressor and the power turbine was also abandoned when it failed to show a net advantage in efficiency. The third configuration required separate combustors for the power turbine and the gas producer turbines but the cooling air requirements for two high temperature turbines decreased any attractiveness of this cycle.

## 3.6 ICR COMPONENTS

All of the ICR systems that have been evaluated, including both the one- and two-spool arrangements, have essentially the same components. Each component is described below, in the order that it is encountered by the air passing through the engine.

### 3.6.1 Low Pressure Compressor

A split compressor is an essential feature in an intercooled engine. In the one-spool arrangement both sections are located on the same shaft, while in the two-spool configuration they are driven separately. The low-pressure (LP) compressor for both the one- and two-spool configurations is an axial-flow design, generally with three to five stages (approximately 3:1-to-3.7:1) for a total engine pressure ratio between 12:1 and 16:1. Variable inlet guide vanes and variable second-stage vanes are typically used in this low-pressure section to allow both starting and low-power operation to be accomplished efficiently. These vane angles can be adjusted to match the required flow vectors at the lower rotational speeds associated with part-power conditions and starting. The compressor operating conditions are moved away from surge through the use of such variable geometry. Advanced "controlled diffusion airfoil" design techniques will be used in developing the blading for these compressors. This will provide the very high polytropic efficiencies needed by the ATS to meet the overall engine performance goals. Long chord blade designs will be used and these will minimize the number of blades required and provide a more robust compressor system.

In the one-spool arrangement, the exit of this low-pressure section will have a valve to allow air to be bled from the system into the engine exhaust for starting and possibly part-power conditions. Variable geometry can help, but by itself will be insufficient to prevent surge without air bleed for all conditions. Based upon preliminary analysis, the blades, vanes, disks and casings of the one-spool compressor section will most likely be constructed of standard materials currently used in industrial gas turbines (IGT).

The two-spool has few problems associated with the operation of the low-pressure compressor. Generally both the low- and high-pressure spools stabilize at some speed that is near optimum for the turbine and compressor combination.

### 3.6.2 Intercooler

The air leaving the low-pressure compressor flows into the intercooler through a transition duct that will be designed to have the lowest possible pressure loss. Turning vanes may be used in this duct to reduce the pressure losses. The intercooler cools the air leaving the LPC before entering the HPC, and lowers the temperature of the air leaving the HPC. The lower HPC outlet air temperature allows more energy to be extracted from the exhaust stream per unit heat transfer surface area. A *considerable increase in thermal efficiency is realized when* high-pressure-ratio cycles use intercooling in combination with recuperation.

Two types of intercooler were considered. One is a direct heat exchanger, generally air-to-air, and the second is indirect where a pumped heat transfer medium (e.g., water/glycol) is used. A second heat exchanger is used to cool the heat transfer medium. Solar selected the second type because of its compactness. Topical Report No. 3 gives more details of this decision.

In some hot and humid environments, water may condense within the intercooler and form small droplets in the air stream as the air exits the intercooler. The intercooler will be designed to minimize this occurrence, however, conditions may exist at some locations where water droplets are present in the air stream leaving the intercooler.

### 3.6.3 High Pressure Compressor

The high pressure compressor may be either axial or radial. For an overall engine pressure ratio of between 12:1 and 16:1, the axial HPC section usually has four-to-six stages. The number of stages depends upon the design pressure ratio as well as the efficiency desired for the compression process. On the one-spool arrangement, the high-pressure compressor may have variable inlet guide vanes (VIGVs) to aid in achieving high part-load efficiencies and also an air bleed system at the exit. At the outlet of the high pressure compressor is a transition section that allows the air flowing in the compressor exit annulus to transfer into one or two cylindrical ducts, which convey the air to the recuperator.

Because the air leaving the axial high-pressure compressor has to be turned (through the transition duct) and fed to the recuperator in either one or two circular-sectioned ducts, there will be pressure losses. To minimize the pressure losses, the high-pressure compressor may be constructed as a radial- or centrifugal-type of compressor, rather than the axial type. Although the axial-type compressor generally offers higher compression efficiency, the air-turning process required with an axial compressor can induce high losses that are not found with a radial compressor configuration. In the radial compressor, the air is turned as part of the compression process. The normally lower efficiency of the radial system may actually turn out to be higher than the equivalent axial system when the axial turning losses are included.

### 3.6.4 Recuperator

Solar has had nearly 2 million hours of successful service from a primary surface recuperator (PSR). In addition to its demonstrated reliability, this PSR has been selected for ATS because it offers the combined advantages of high effectiveness, low weight and volume, and low maintenance. Another beneficial feature of the PSR is its noise reduction characteristics. Experience has shown that it can replace standard exhaust silencers.

The recuperator to be used in the Solar ATS50 has a calculated effectiveness of 90%. This effectiveness value is based upon the measured performance of over 50 units operating in the field. This effectiveness can be improved by adding more air cells, provided that the additional size is not detrimental. Increasing the effectiveness results in increased size and cost of the recuperator.

The pressure losses associated with the recuperator are modest. Typically there is a two percent loss on the air side and a four percent loss on the hot gas side. These values do not include the losses from the compressor to the recuperator nor the losses encountered between the power turbine and the recuperator inlet. The pressure losses of the recuperator can be decreased; however, the size of the unit increases in proportion to the decrease in pressure loss.

### 3.6.5 Low Emissions Combustor

A catalytic combustion system has been chosen as the best approach for the ATS50. The low-temperature catalytic oxidation of fuels is considered to be the best technique available to meet the ATS50 goal of eight ppmv NOx. This approach relies on premixing of the air and fuel before it enters the combustor. See Topical Reports 8.2 and 8.5 for more details of this combustor.

## 3.7 TURBINE SECTION

The design of all turbine stages has been optimized for aerodynamic performance, while maintaining mechanical integrity. Both configurations reflect work and flow coefficients which produce optimum efficiency, while accounting for inter-turbine duct losses. The performance of the turbine stages includes parabolic work and loss distributions and three-dimensional aerodynamics. The final design of the turbines will reflect a concurrent engineering effort among aerodynamics, heat transfer, mechanical design, and manufacturing disciplines, with the goal being optimum cycle efficiency at industrial turbine system life requirements.

### 3.7.1 Gas Producer Turbine Section

This section may consist of one or two turbines (see Figures 1 and 2). All gas producer vanes and stationary gas-path hardware will be uncooled ceramic material. By uncooled it is meant that the vanes will not be internally cooled, however, compressor bleed flow will be available for the purpose of cooling ceramic-to-metal interfaces and to reduce thermally-induced stresses related to the gas-path temperature profile. Internally-cooled ceramic and film-cooled metal vanes are considered lower risk back-ups to the uncooled ceramic.

At this point, the gas producer turbine blades will be cooled, directionally solidified or single crystal. Technologies developed in the CSGT program will be phased into the ATS50 leading to cooled ceramic blades. However, in an effort to control risk and satisfy market introduction timing, Solar has elected to begin with cooled metallic blades.

A dual-property disk will be used as the mounting platform for the gas producer turbine blades. The dual-property disk, which consists of a cast superalloy outer rim hot isostatically pressed (HIP) bonded to a more conventional forged material inner disk, allows for operating at rim temperatures of approximately 1500°F, while maintaining life requirements (see Topical Report No. 8.4). The disk will still require cooling; however, it will be at a reduced level. The higher allowable rim temperature is necessary due to the flat radial profile of the catalytic combustion system. This flat radial profile is also important in facilitating the application of ceramic turbine airfoils.

### 3.7.2 Power Turbine Section

The power turbine consists of three stages on a free shaft. The first stage has an uncooled, ceramic variable vane and a cooled, directionally solidified or single crystal blade. The variable vane allows for maximizing system efficiency at part-load and non-standard day ambient conditions. Stages two and three are uncooled metallic vanes and blades. The power turbine of the one- and two-spool configurations differ only by the level of cooling required in the first stage.

## 3.8 CONFIGURATION AND CYCLE SELECTION

Though several different engine configurations were investigated, the only configurations which looked promising from an overall efficiency, operability, and cost standpoint were the one-spool and two-spool gas producer, intercooled, and recuperated (ICR) engines. Reheat combustors and autothermal reforming were not considered at this stage of the analysis, as these will be added to any of the ATS 50 engines to obtain the ATS 60 engine.

The first step in determining which cycles most closely met the program goals for these one-spool and two-spool configurations was to perform cycle optimization studies. In these studies TRIT, PR, and compressor work split were varied to determine which combinations gave the best overall efficiency. The compressor work split is the combination of LPC and HPC pressure ratio giving the overall compressor pressure ratio. Figures 3 and 4 show plots of efficiency vs. PR at lines of constant TRIT for both the one-spool and two-spool configurations of the engines.

In addition to the basic design point optimization, sensitivities of some of the cycles to changes in component efficiency, cooling, pressure losses, etc., were determined.

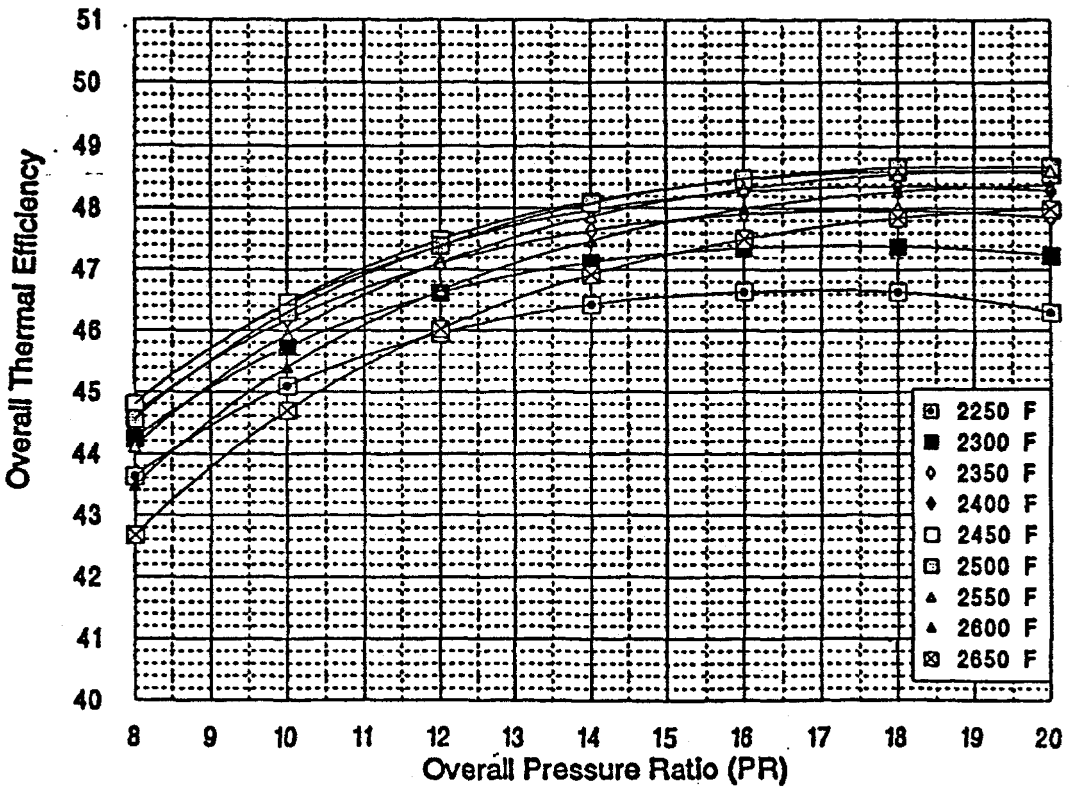



**Figure 3. Overall Thermal Efficiency vs. PR at Lines of Constant TRIT - Two-Spool Configuration. The optimum efficiency is shown to be between Rc of 18:1 to 20:1, with a TRIT of 2500°F.**

## 3.9 CRITICAL TECHNOLOGIES

Four components were identified as critical to achievement of the goals of ATS50. These were:

1) the high temperature GP turbine blades,
2) the recuperator,
3) the intercooler, and
4) the low emisisons combustor.

### 3.9.1 High Temperature GP Turbine Blades

They might be either cooled ceramic or cooled metallic single crystal blades. The ceramic configuration resulted in the lowest cooling flow budget, however, there may be a somewhat higher degree of risk associated with using ceramics in rotating components. This design approach will be carried as a back-up until ceramic technology, being developed at Solar (under the Ceramic

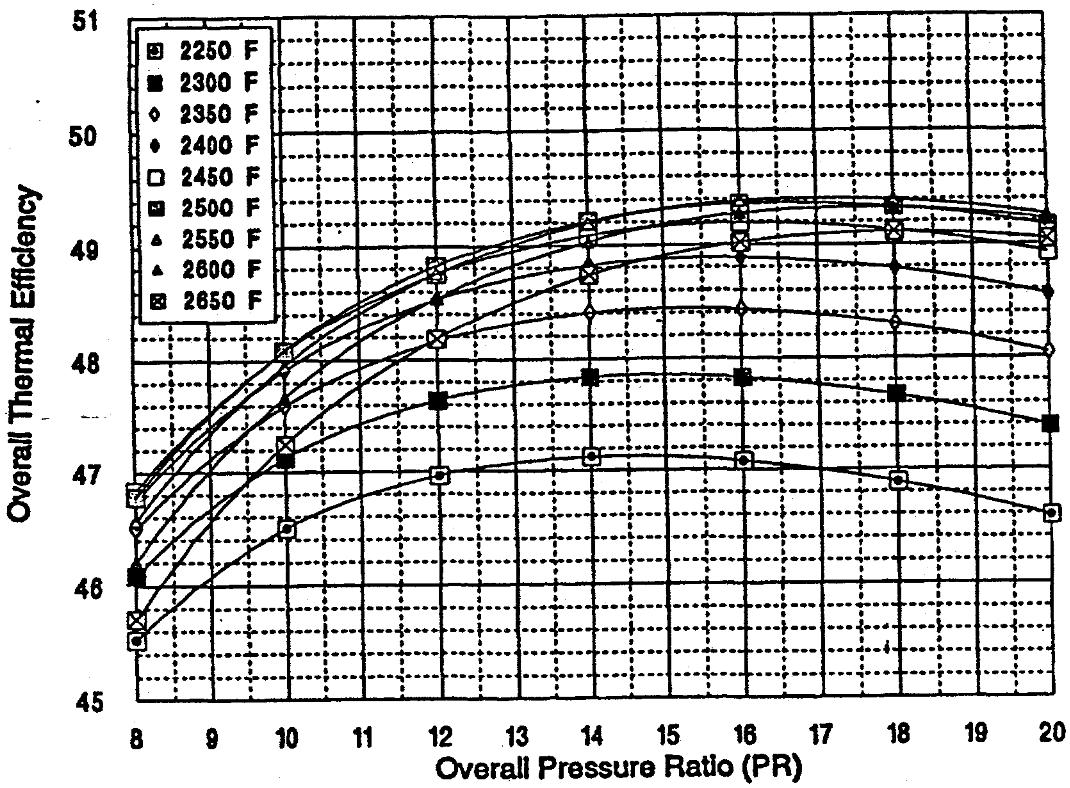



**Figure 4. Overall Thermal Efficiency vs. PR at Lines of Constant TRIT One-Spool Configuration. The optimum efficiency is shown to be at an Rc of 16:1, with a TRIT of 2500°F.**

Stationary Gas Turbine D.O.E. program) and elsewhere, can be confidently applied to high temperature rotating parts. On the basis of potentially higher durability and lower risk, the proposed ATS50 gas producer and power turbine first stage will consist of metallic blades.

The GP turbine blades have a combined film, impingement, and convection cooling circuit typical of that used in aircraft jet engines. The most significant feature of the GP blade cooling system is the "shower head" film cooling holes around the leading edge. This method of cooling was required due to the catalytic combustor flat profile and the high relative gas temperature.

### 3.9.2 Recuperator

The extensive prior experience with the PSR made this less important in the success of the ATS, except in the important aspect of recuperator life and hence LCC (life cycle costs).

### 3.9.3 Intercooler

The effectiveness of the intercooler is an important factor in providing near isothermal operation. The intercooler will be of the indirect type that employs a water/glycol mixture as a heat exchange medium. The heat exchanger located between the two compressors, is linked by a water/glycol loop to a second heat exchanger. This second heat exchanger transfers the heat in the water mixture to the ambient air or to some other heat sink such as a body of water. This combination of two heat exchangers that ultimately transfers heat from the low-pressure compressor discharge to ambient usually has effectiveness limits typically between 0.7 and 0.85. While, at first glance, the intercooler effectiveness may be critical to maximum cycle efficiency, the return is highly dependent upon the cycle pressure ratio. For our studies, a one percent change in intercooler effectiveness translates to an overall cycle efficiency change if 0.075%. The overall effect of a 70-to-85% intercooler effectiveness change would increase the cycle efficiency by only 1.125%.

Reducing the heat rejection sink temperature can improve the intercooler effectiveness. If the sink temperature can be lowered below ambient the effectiveness can be increased. If the secondary cooler is a cooling tower using evaporative cooling, it can reduce the water temperature to within five degrees of the wet bulb temperature. At ISO conditions the dry bulb temperature is 59°F and the wet bulb temperature is 52°F. At these conditions, the cooling tower can maintain the water temperature at or below the ambient dry bulb temperature. However, approximately 40 gallons-per-minute of make-up water would be needed for an ATS cooling tower.

### 3.9.4 Catalytic Combustion System

This is a critical component. Topical Reports 8.2 and 8.5 should be reviewed for details.

# Section 4

# CONVERSION TO COAL

This work constituted W.B.S. 2.4 on the ATS Program. Topical Report No. 4 should be consulted for details of this work.

It should be noted that it has become clear in the 1990's that earlier scenarios restricting use of natural gas were too pessimistic. The decade in which natural gas will become scarce has moved ahead by at least twenty years. Nevertheless, the DOE and Solar have reviewed this situation and have explored the possibility that the more plentiful fuel, coal, may need to replace natural gas before the useful life of the ATS units have been exhausted.

## 4.1 INTRODUCTION

The feasibility of a coal-derived fuel for firing the ATS was explored for the 5 MW ATS. Three approaches have been considered: direct-fired combustion using either a slagging combustor, or a pressurized fluidized bed (PFBC): externally or indirectly fired approaches using pulverized fuel; and external gasification of the fuel with subsequent direct combustion of the secondary fuel. Each of these approaches requires substantial hardware and system modifications for efficient fuel utilization. The direct-fired approach has been demonstrated by Solar with a full size coal-water-slurry fired combustion system. In parallel with this program the DOE funded the development of integrated gasification combined cycle systems (IGCC). The integration issues with each type of firing are discussed in the sections below.

The 5 MW ATS is a recuperated engine and may have a catalytic combustor. The significance of the recuperator for the purposes of conversion to coal firing is that the engine will use external ducting to take the air from the compressor section to the recuperator and then back from the recuperator to the turbine section. This external ducting provides great flexibility allowing large stand-alone combustion schemes or externally fired heat exchange systems to be connected in place of the catalytic combustor. Although the engine can be readily adapted, there are likely to be some materials of construction problems with the ducting that leads to the turbine section because of the high temperatures and pressures plus the corrosiveness of the combustion products from coal-derived fuels.

## 4.2 DIRECT FIRED SYSTEMS

### 4.2.1 Coal-Water Slurry

At Solar the development of direct firing of a gas turbine with coal water slurry (CWS) was pursued under the aegis of a cost shared DOE contract. The system chosen shown in Figure 5 included a rich primary zone and a lean secondary combustor zone. The combustor for a 4-MW engine is shown in Figure 5 without the hot gas cleanup filter (HGCF). The slag produced by the ash in the coal was aerodynamically removed in the primary zone and in a component between the primary and secondary called the particulate removal impact separator (PRIS). This latter component consisted of staggered rows of rods which served to create a series of orifices and particle impaction sites. Much of this design was based on previous work done for DOE's Pittsburgh Energy Technology Center. Between the primary zone and the PRIS over 90% of the slag was removed. The primary

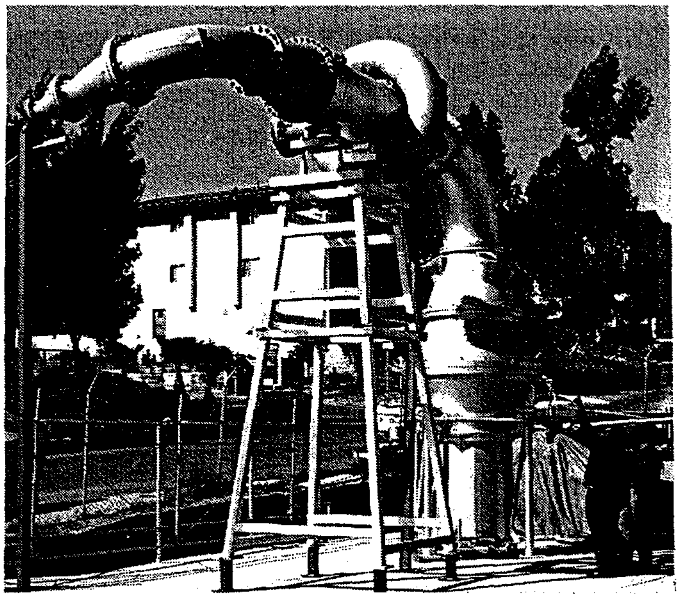


**Figure 5. Full Size Centaur Coal Combustor**

zone design equivalence ratio was approximately 1.3 which resulted in NOx results as low as 30 ppmv corrected to 15% oxygen. The system was designed for the Solar Centaur 50 engine which has a combustor inlet temperature of 606°K (630°F). The cycle data for the Centaur 50 and the ATS are listed in Table 4. For the data in Table 4 the primary zone outlet temperature, (the inlet temperature to the PRIS) was 1760-1870°K (2700-2900°F).

Since the cycle chosen for the ATS engine includes a recuperator the combustor inlet temperature will be high on the order of 870°K (1100°F). This high inlet temperature will be reflected in a high combustor primary zone temperature that would be in the range of 3440-3640°K (3170-3370°F). This increase in temperature will require considerable additional work to clean up the combustion gas especially for particulate removal in the PRIS, for sulphur removal, and for NOx control in the rich-lean combustor.

**Table 4. Combustor Operating Conditions**

| Parameter | Centaur 50 | ATS |
|---|---|---|
| Air flow, kg/sec (pps) | 18.6 (41) | 15 (33) |
| Inlet Temperature, °K (°F) | 606 (632) | 874 (1114) |
| Outlet Temperature, °K (°F) | 1284 (1851) | 1481 (2206) |
| Inlet Pressure, kPa (psia) | 1046 (151.6) | 869 (125.9) |

### 4.2.2. Other Coal-fired Systems

Both dry coal and a pressurized fluidized bed combustion (PFBC) were examined. In both cases, control of emissions and particulate blocking of the recuperator were felt to be insuperable problems.

## 4.3 INDIRECT- OR EXTERNAL-FIRED SYSTEMS (EFS)

A second approach to the use of coal and biomass fuels in a gas turbine is the externally-fired combustor. Using this technique the solid fuel is burned in an atmospheric combustor system. The exhaust leaving this combustor is passed through a heat exchanger before being exhausted to ambient. The stream to be heated in the heat exchanger by the exhaust is the air from the discharge of the gas turbine compressor. This air after heating is delivered to the turbine inlet section. Since the ATS engine already incorporates a recuperator, external ducting to and from the main engine exists. In this particular instance the recuperator would be replaced with the heat exchanger section of the EFS using modified external ducting. In this system the exhaust of the combustor is separated from the turbine so that none of the potential contaminants and particulates pass through the turbine thus solving some of the corrosion and deposition problems. There are, however numerous other problems with this approach for the turbine. To heat the air to the desired turbine inlet temperature of approximately 1481°K (2206°F) the heat exchanger materials of construction must be capable of operating at slightly higher temperatures. Ceramics may be shown to be suitable but very large heat transfer surfaces are needed.

Operational problems would be acute. These are related to the high thermal mass and meeting variable power demands. Such constraints were found to remove the indirect- or externally-fired system from further consideration.

## 4.4 GASIFICATION

There are many processes available that can be used to gasify both coal and biomass. Many of these processes have been in use for a number of years. Generally the gasification processes consist of either pyrolysis alone or pyrolysis combined with some form of char gasification. The char, always produced when coals or biomass are pyrolysed, can be converted to gases through reaction with steam and/or oxygen. The reaction with steam is endothermic while that with oxygen is exothermic.

In most gasifiers the thermal energy required to gasify the solid fuel is supplied by the combustion or partial combustion of part of this fuel. When these two reactions are thermally balanced the gasifier can produce high levels of hydrogen and carbon monoxide. The lower heating value of the secondary gaseous fuel produced depends largely on whether air or oxygen is used as the oxidizer in the combustion process. When air is used for (partial) oxidation and cracking the product is usually a low energy gas (LEG) because the nitrogen in the air acts as a diluent. Pure oxygen blown approaches produce medium energy (MEG) gases.

Other gasification approaches include hydrogasification. This technique employs pyrolysis of the primary fuel in an atmosphere of hydrogen or in a mixture of steam and hydrogen. This type of gasification can produce a product gas with high levels of hydrocarbons and this usually provides the highest lower heating values.

In most cases the infrastructure required for these reactors is such that it does not make economic sense to provide one reactor for a single 5-MW turbine. To consider these gases as viable fuels for the ATS a supply of gas from a central reactor would have to be assured.

## 4.5 DISCUSSION AND CONCLUSIONS

The main conclusion reached in this study of converting the GFATS into a CFATS is that gasification is probably the only practical approach. The combustion of coal and biomass in a recuperated engine will require the conversion of the solid fuels to secondary gaseous fuels.

This conclusion will have an effect on ATS design. The external duct sections (to and from the recuperator) will have to be so arranged that they can be easily modified or replaced. This will build-in the conversion capability of the GFATS to a CFATS configuration. The necessary combustion section needed to handle gaseous fuels derived from coal and other biomass substances will be mounted external to the ATS using the available external duct connections.

# Section 5

# MARKET SURVEY

This work constituted WBS 2.5 on the ATS Program. Topical Report No. 5 should be consulted for details of this work.

## 5.1 INTRODUCTION

This market study of the Gas Fired Advanced Turbine System examined the economic and siting constraints of the ATS compared with competing systems in the various candidate markets. The advances in performance to be achieved will permit expansion of the domestic and foreign markets in Solar Turbines Incorporated traditional market in the Oil and Gas and Industrial Power Generation industries. In addition, the performance increases will permit growth in a major new marketplace to supply generating units for distributed electrical power.

The ATS will reduce the cost of power by at least 10% below today's generation systems, and will offer a level of reliability, availability, maintainability and durability that customers of Solar's dependable equipment have come to expect. In addition, the ATS will operate at thermal efficiencies at least 15% higher than 1991 products, and with emissions not exceeding 9 ppmv NOx, and 20 ppmv CO and UHC. Driven by an optimized recuperated gas turbine engine, the first ATS system will deliver thermal efficiencies of up to 43.2%. This advanced turbine system will be flexible enough to meet the different operational requirements of a wide variety of commercial/industrial market applications.

An important characteristic expressed by Solar's customers is some conservatism before investment of several million dollars for equipment. This conservatism has been found to take two forms. One is the need for operational data over an extended period to convince these customers of the basic product integrity and performance. The second has been the need to avoid major increments in operating conditions such as TRIT. These factors have been assumed to apply to the introduction of ATS to Solar's customers in the company's traditional market in the Oil and Gas Industry, as well as to new markets such as the growing demands for distributed power. This factor has been an important consideration in selection of the cycle and design of ATS.

In addition to the traditional marketplace and the new marketplace for distributed power, application of ATS technologies will spin off to benefit current Solar products, and will be deployed into the large pool of existing equipment through retrofit and upgrades to improve the performance of existing equipment already in the field, multiplying the environmental and performance benefits.

## 5.2 MARKET SURVEY

### 5.2.1 Organization and Planning

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. Appendix A of Topical Report 5 presents their report.

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. Appendix B of Topical Report 5 presents their report.

Solar Marketing provided an independent source of data that was based on 30 plus years of commercialization. This report combines data from these three sources.

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 marketplace of such a size and cycle.

The researchers, in the course of their study, contacted many potential customers. They identified several drawbacks to the cycle, cost and size of the intercooled, recuperated engine that was the initial selection. These drawbacks have been summarized in Topical Report No. 5, Figure 1 and Table 1 to which reference should be made for the details. Suffice it to say at this point that the intercooled, recuperated cycle had several negative features (first cost, schedule risk, lower RAMD, reduced fuel flexibility, customer acceptance, and others). All of these negative features were substantially mitigated with the simple recuperated cycle. Ultimately, the optimized recuperated cycle was selected as the first ATS model to be delivered in the year 2000. It most closely aligned with market segments without compromising the ATS program goals.

### 5.2.2 Market Segments

Acceptance of the ATS by Solar's traditional customers in the Oil and Gas Industry was essential before considering acceptance by new markets. The needs of the Oil and Gas Industry will be surveyed first.

#### 5.2.2.1 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%, 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 than in pipelines. 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 increasing the use of reduced manning with remote operation will become important management and operation goals within the gas industry. Downtime of equipment must be avoided at all costs.

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 many driver/ compressor purchasing decisions. There is some sentiment within the industry that electric drives may be the only practical solution to some local siting problems.

Another major change affecting the natural gas industry is the increased stringency of air emissions regulations. Notably the 1990 Clean Air Act Amendment (CAA) has improved the perceived desirability of natural gas as a fuel choice. It also has imposed control requirements on compressor station operators that represent major hurdles and cost implications. The primary objective of the CAA legislation with regard to the pipeline industry was to impose Lowest Achievable Emission Rate (LAER) for compressor station emissions on a case-by-case basis.

The primary application opportunity in the oil and gas industry for Solar's ATS lies within natural gas compression and oil transmission pumping. Presently, there are over 7,700 compressors currently in use in natural gas compression applications. Approximately 85% of these natural gas compressors utilize reciprocating engine drivers.

The major purchasing factors, in order of importance are: capital cost, environmental performance, operating costs, efficiency and siting. Of these, capital cost and environmental were significantly more important than the other criteria.

#### 5.2.2.2 Electrical Power Generation

This 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 mix of the types of utilities and their electrical production is presented in Table 5.

Independent power producers generate nearly 5% of the electricity in the U.S. This power is almost exclusively sold to electric utilities and is included in Table 5. As a result of the Public Utilities Regulatory Act of 1978 and implementation of FERC and state regulations, electric utilities may (and sometimes are required to) purchase electricity from non-utility generators (NUGs). As a result of the 1992 Energy Policy Act, NUGs and electric wholesale generators (EWGs), can compete with traditional utility electricity generation. Each segment of this realigning U.S. electric power industry – electric utilities, NUGs and EWGs – are candidates for the ATS in most, if not all, applications.

The electrical power industry is undergoing a fundamental change in moving toward deregulated generation and competitive market for power supply that will successfully challenge the traditional view of an integrated (generation-transmission-distribution) utility that operates as a legally franchised, regulated monopoly. NUGs have become an increasingly attractive economic alternative

**Table 5. Types of Utilities in the United States**

| Utility | | Customers (Millions) | Production | |
|---|---|---|---|---|
| Type | Number | | GWh | % of U.S. |
| Privately owned | 260 | 86 | 2114 | 76 |
| Public owned<br>State & Municipal<br>Federal | <br>2024<br>10 | <br>15.6 | 445 | 16 |
| Local Coops | 941 | 12.0 | 207 | 7.5 |
| **Total** | **3235** | **113.6** | **2766** | **99.5** |

to large central station utility-owned power plants. With wholesale and retail wheeling and more utility size "merchant plants", utilities are afforded the opportunity to purchase power at or below their cost. The days of "bigger is better," the primary justification of a regulated monopoly, are long over. More recently, the Clean Air Act Amendments of 1990 and the Energy Policy Act of 1992 have offered additional changes that will promote the economic competition of NUGs. As a result of these facilitating regulations, NUGS have increased tremendously in the past 15 years, with an outlook of continued growth for the future.

These legislative developments, along with changes in market forces have opened a viable commercial market opportunity for smaller-scale, gas turbine systems capable of providing efficient, reliable and relatively inexpensive electrical power.

The concept of distributed power has widened the opportunities for small units of the size planned for ATS. Many of the large cogeneration units installed in the 1980's provide power directly to a utility. Distributed power involves small units within close proximity to the user to provide increased efficiency over central power plants, reduced transmission losses, reduced pollution, increased reliability, and lower cost. These advantages become clear when a coal-fired unit forced to locate hundreds of miles away is compared with a local installation.

In sum, the electric power generation markets represent the largest potential markets for the ATS due to the competitive response underway to deregulation and the onset of distributed power generation supplementing larger, more centralized power sources.

### 5.2.2.3 Prime Movers

Two other markets were surveyed: industrial prime movers; and marine propulsion.

### Industrial Prime Movers

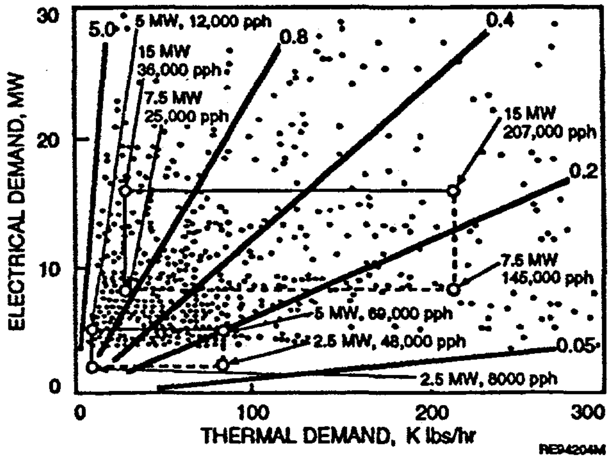
The industrial sector accounts for more than 36% of total end-use energy consumption. Process heat accounts for the largest share of energy consumption industry overall, and mechanical shaft drive represents another large use of energy in many industries.

A recuperated gas turbine provides a high electrical-to-thermal (E/T) ratio of outputs with a moderate exhaust temperature from the recuperator. Hence less process steam is available as compared to a simlarly sized simple cycle gas turbine (unless auxiliary firing is used). However, the exhaust from the recuperator has a high oxygen content. A duct burner and heat recovery steam generator can provide a wide range of E/T ratios as illustrated in Figure 6.

Topical Report No. 5 provides more discussion of the industrial prime mover market.

### 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. The high shaft efficiency is a distinct advantage in meeting the needs of this market. Other advantages of the ATS will be the high power-to-weight ratio because the principal competition comes from heavy reciprocating engines with thermal efficiencies in the range of 39 to 44%. 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.




[1]Operation to 50% load is assumed and duct burner firing in the recuperator exhaust down to 3 percent oxygen. Lines show electrical-to-thermal output ratios of 5.0; 0.8; 0.4; 0.2; and 0.05. Dots show individual industrial plant requirements in USA above 4MW and above 10,000 pph of steam.

**Figure 6. ATS Outputs in MW and Pounds Per Hour of Steam[1] for 5 and 15 MW Units**

The passenger carrying vessels currently have a total installed power of 8-10 MW and the larger car and passenger vessels have a total installed power of 20-40 MW. With these power plants typically consisting of two separate engine rooms, there is a good fit between the needs of these vessels and 5 and 15 MW marine gas turbines.

The principal disadvantage of the ATS in this market is the need to use liquid fuels rather than natural gas. This may delay market development of this market to beyond the year 2000.

### 5.2.2.4 Other Markets

Solar's traditional, major source of customers have been in the oil and gas industry. This market segment has been reviewed earlier, followed by the new market segment for ATS of electrical generation especially in the form of distributed power. Application of ATS to prime movers in both industrial and marine markets is presented in the last of the preceding sections.

A significant number of applications of Solar's gas turbines has occurred in a large number of industries including bakeries, hospitals, prime metal extraction plants, glass works, institutions, and so on. It is expected that these opportunities to apply the ATS technology to such installations will be increased as a result of the cost and performance benefits of ATS over simple cycle gas turbines. Topical Report No. 5 contains surveys of selected industries to show how the advantages of ATS will increase the acceptance of the industrial gas turbine in such applications. Reference should be made to this report for more details.

The primary metal industry was the third largest user of energy in 1985 consuming 3.23 quads (quadrillion Btu) or about 15% of the total manufacturing sector. One of the biggest factors opening access to this industry will be environmental concerns because of the large use of coal and derived products. Opportunity for the ATS within the primary metal industry is good, given the increasing trend toward electrification. Each industry segment may not be growing rapidly, but there is a structural shift occurring, particularly within the steel industry, favoring the industrial ATS between the 5 and 20 MWe size range.

The fabricated metal industry uses less than 2% of the total primary energy in the manufacturing sector. Paper and allied products use 2.21 quads or 12.6% of the manufacturing sector energy consumption. Textiles, chemical industry, and petroleum refining were other industries surveyed. Few generalizations could be made because the fit of ATS will be dependent upon matching the electrical/mechanical drive and thermal energy requirements of a specific process or plant. However, the advantages of ATS over the simple cycle gas turbine will increase the potential for penetration in these industries.

Another potential market providing an expanded market opportunity is in the commercial field. Energy efficiency will come increasingly under watch by commercial and large residential building facilities where central physical plants represent potential opportunities for cogeneration and for prime mover driven cooling equipment. Steam can be used from recovered exhaust heat for such things as space heating, domestic hot water and absorption cooling. According to the EIA, buildings on multi-building facility sites accounted for 50% (2.9 quads) of the energy consumed in all commercial buildings in 1989.

### 5.2.3 Competing Equipment

Within the utility, industrial, commercial/residential, mechanical drive and transportation markets, the industrial ATS will compete with several technologies. The primary competition for the ATS includes the following: simple cycle gas turbines, combined cycle gas turbines, cogeneration, reciprocating engines, and fuel cells.

#### 5.2.3.1 Simple Cycle Gas Turbine

The simple cycle gas turbine is the primary combustion turbine the ATS would replace. These machines have thermal efficiencies in the range from 32-26% at the shaft. They have good power-to-weight ratios and small footprints in the range of 5 to 300 kW/sq. ft. The ATS will have modestly higher capital cost than a simple cycle, but that will be outweighed in most applications by the increased performance. The simple cycle turbine presently is used in utility peaking, industrial cogeneration, mechanical drive, and high speed marine applications. The ATS will be very attractive in all of these applications, and would be best used as an intermediate or base load distributed generator for the utility applications.

#### 5.2.3.2 Combined Cycle Gas Turbines

Solar has operated combined cycles based on Solar gas turbines that fall within the range of sizes planned for ATS. Remote operation has been achieved on such units. However, the general experience has been that the customer has little interest in the complexity associated with two pieces of rotating equipment plus a boiler and additional controls. It is not expected that combined cycles will compete with the ATS for distributed power in small units.

#### 5.2.3.3 Cogeneration Systems

A cogeneration system may comprise a heat recovery steam generator (HRSG) behind either a simple cycle gas turbine or a reciprocating engine. The system with a simple cycle gas turbine provides a medium value for E/T because of the high temperature and high flow of the exhaust. The reciprocating engine provides a very high value of E/T because the exhaust flow is limited and the temperature is low (although jacket water may be used to generate hot water). The ATS will offer a value of E/T between these limits.

Competition between ATS and cogeneration systems may occur in a few specific niches where the type and quantity of heat required can be matched to the output of the ATS. Cogeneration will not be a factor in the case of distributed power.

#### 5.2.3.4 Reciprocating Engines

The ATS will raise the thermal efficiency of the gas turbine to match that of the best reciprocating engines in the size range around 5 MW. The advantages of the gas turbine; viz., small footprint, minimum vibration, low weight, much reduced pollution, and ease of installation will make the ATS much more competitive. In general, older reciprocating engines for pipelines are gradually being retired or retrofitted. Sales of reciprocating engines continue to decline. R&D efforts to improve this technology are concentrated primarily on improving emissions performance to delay replacement.

#### 5.2.3.5 Fuel Cells

Fuel cells have been promising performers for many years, and their competitive position has been difficult to evaluate. Some appear to regard fuel cells as positioned where industrial gas turbines were 20 years ago. Table 6 presents a comparison of fuel cells and ATS. It is recognized that ATS will not be available for several years, but the fuel cell reflects current technology.

Solar believes that the ATS will remain competitive with the fuel cell for the foreseeable future. Two reasons for this belief are: (1) the fuel cell needs to operate a reformer to convert methane to hydrogen; and (2) the loss of performance as the high activity required in the electrodes deteriorates with time.

#### 5.2.3.6 Comparison of Systems

Some comparison has been made in the previous sections to illustrate the differences between competing equipment. Table 7 extends this comparison for some competing systems for electrical generation on four important performance factors. Competing systems for distributed power range from storage batteries to fuel cells sited locally. ATS will be competitive in these markets, especially when transmission and distribution costs are considered.

In general, it has been concluded that ATS will be most cost competitive in electric power distributed generation, peaking and intermediate applications, and in mechanical drive for the manufacturing and the natural gas and oil production and transmission industries. This is principally attributable to the fact that competitors with equal and greater efficiencies are also more expensive to purchase and maintain.

**Table 6. Comparison of ATS With Fuel Cells**

| Factor | Fuel Cells | ATS |
|---|---|---|
| Emissions (NOx) | 1-4 g/GJ | 5 ppmv NOx (equal to 7 g/GJ) |
| Electrical Efficiency | 40-50% (low voltage D.C.) | 42.8% (high voltage AC) |
| Overall Thermal Efficiency | 80% (82°C hot water) | 91% (103 Mpa steam) |
| Cost (1992 Dollars) | ~$3000/kWe | $650/kWe |
| Footprint | 0.23 $m^2$/kWe | 0.042 $m^2$/kWe |
| Noise | Low (mainly reformer) | Low (Recuperator) |
| Load Following | Moderately good (limited to slow rates of load change) | Excellent |
| Fuel Flexibility | Limited ($H_2$ or reformed $CH_4$) | Good |
| Scale-up/Technology Transfer | Thermal management difficult | No problems |
| Reliability/Availability/Maintainability | Poor, under evaluation | Good |
| Operating Costs | Round the clock operation of reformer system currently required | Can be operated without personnel |
| Start-up | Typically 8 hours | Less than 5 minutes |

In the case of distributed power, it has been concluded that the ATS will offer the most environmentally friendly installation. There are significant advantages for a distributed power unit located in residential or commercial areas. Without additional silencing, the ATS will be quiet (85 dba at 3 m for the recuperated version, without additional silencers), have lower emissions (8 ppmv NOx, 10 ppmv CO and 10 ppmv UHC) than local traffic. ATS will also be safe (contractors digging into local power and gas lines present a greater source of problems).

## 5.3 TRENDS IN THE LARGEST POTENTIAL MARKETS

### 5.3.1 General Trends

Trends in the potential markets for ATS must be recognized and analyzed to develop market strategy and to estimate market potential. Four market areas will be examined in more detail:

(1) Utility
(2) Oil and Gas
(3) Cogeneration
(4) Commercial

In the previous sections industries were examined to assess their potential for cogeneration units; here, general trends in cogeneration that are common to all industries will be examined.

The strongest, single trend is the growing importance of low emissions to customers making equipment purchase decisions. Availability has consistently been – and will remain for the

**Table 7. Competing Systems for Electrical Generation[1]**

| System | Availability (%) | NOx Emissions (ppm) | Installed Cost ($/kW) | Thermal Efficiency (%) |
|---|---|---|---|---|
| ATS | 98 | 5 | 650 | 43.2 |
| ATS + HRSG | 98 | 5 | 1000-1100 | up to 74% |
| Simple Cycle Aeroderivative | 92 | 25 | 718 | 39 |
| Simple Cycle GT Heavy Duty | 92 | 25 | 550 | 28.7 |
| GT-Combined Cycle | 92 | 9 | 700 | 58 |
| GT-Chem Recup/Reheat/Inter-cooled | 90 | <5 | 850-1000 | 57.2 |
| Storage Battery (5 hour) | 91 | 0 | 804 | 86.2 |
| Gas Boiler/Steam Turbine | 95 | 25 | 600 | 35 |
| Conventional Gas Turbine | 95 | 25 | 650 | 34.5 |
| Phosphoric Acid Fuel Cell | 91.6 | Trace[2] | 3000 | 41.1 |
| Molten Carbonate Fuel Cell | 97 | Trace[2] | 3000 | 52.9 |
| Reciprocating Gas Engines | 91 | 42 | 600 | 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.

foreseeable future – the paramount technical buying criterion because equipment downtime has the greatest adverse cost impact. Efficiency affects the cost of power through the cost of fuel. Fuel cost is the largest component of cost for any system running a high duty cycle.

### 5.3.2 Trends in the Utility Market

The utility market is defined as any power producer whose primary interest is in selling power to others. Utilities are undergoing significant changes in structure and the way they perform their business. It is clear that large, central station power plants will continue to dominate the majority of U.S. generation capacity. However, it is also clear that distributed generation will play a more significant role in utility power generation.

Utilities generally separate generation capacity into three categories: Baseload, Intermediate and Peaking. Base load units operate almost continuously and are usually the utility's least expensive and largest central stations. These do not operate efficiently at part load. The peaking plants have low annual operating hours, short start up times, low capital cost, but high operating cost. The characteristics of intermediate generators fit somewhere between the other two load types. ATS will be a good candidate for the traditional utility intermediate load market, and will also find significant application in peaking and base load.

During the 1970's, a number of market events occurred which caused a reversal in electric utility economic trends. Contributing factors were the energy crises of 1973 and 1978, increased environmental control costs, significant over-capacity, stalled or delayed nuclear plant construction, and escalating non-fuel Operation and Maintenance (O&M) costs for coal and nuclear plants. The bottom line was a doubling of electricity prices in real dollars.

These trends, coupled with ever-increasing environmental pressures, induced major legislative and regulatory initiatives which altered the course of the electric industry. This restructuring of the electric utility industry included such gross changes as "unbundling" generation, transmission and distribution functions, and "retail wheeling" for electricity. The effect of this restructuring is not yet clear. Even the Stock Market has not yet identified which utilities will benefit most from these changes. Hence, market analysis remains difficult at the present time, as pointed out by one of Solar's market consultants.

Nevertheless, there is general agreement that distributed power will find increasing adoption in the years ahead. Some factors influencing this trend are: (1) phasing out of nuclear power plants; (2) prohibitive approval schedules for new coal-fired plants; (3) transmission losses (variously estimated at 7-15%); (4) increasing need to supply high quality electricity free from distortions in the sinusoidal wave; (5) increasing competition for energy services at the retail level; (6) increasing need to avoid brownouts where overloaded lines increase transmission losses and reduce quality of electricity; and many other factors related to the industry restructuring discussed earlier.

The decline in supply due to retirement of older nuclear and coal-fired plants will be an increasingly important driver. For example, nuclear power produces 21.75% of all electricity generated by utilities (see Table 1) and all of this will need to be replaced in coming years if present trends continue. Several large nuclear power plants are due to be retired within ten years.

On the other hand, demand for electricity tends to exceed the Gross Domestic Product. For example, one demand forecast published in the 1992 Electricity Report (ER 92) by the California Energy Commission predicted that between 2000 and 2010, the State of California will experience a growth in its peak summer demand increasing from 59 Gigawatt (GW) in 2000 to 70 GW in 2010, averaging approximately 1.1 GW per year.

In addition to predicting the growth in demand, the ER92 contains a resource expansion analysis that develops a list of recommended capacity expansion projects to meet the growing electricity demand. ER92's forecasted resource additions indicates 4 GW of natural gas fired generation capacity will be installed between 1996 and 2003, corresponding to an average of 600 MW per year.

### 5.3.3 Trends in the Oil and Gas Industry

The oil and gas industry opportunities for ATS are primarily in oil and gas production and transmission industries. Opportunities in related industries, such as in petroleum refining tend to fall within the category of cogeneration.

#### 5.3.3.1 Trends in the Natural Gas Industry

Major changes in the U.S. natural gas pipeline industry over the past ten years, including deregulation, have significantly changed the course of the selection and construction of new pipeline technologies, and has opened significant opportunities for the ATS. Until recently, the industry was tightly regulated, and costs were simply passed along to customers. Efficiency was relatively unimportant. Deregulation of the industry dramatically changed this scenario. A series of orders issued by The Federal Energy Regulatory Commission (FERC) effectively converted pipeline companies into gas transportation competitors, focusing these companies' attention on operating efficiencies and cost reductions. Reducing maintenance and energy costs, and increasingly turning to remote, unmanned operations, will gain importance in considering equipment replacements within this newly-directed industry.

The primary natural gas industry ATS application lies within natural gas compression and oil transmission pumping. Over 7,700 compressors are currently in use in natural gas compression applications, many of which are still in service after 40 years of operation, due to the extreme conservatism in design philosophy that drove early driver/compressor designs.

The gas industry faces a need to repower existing compressor stations as efficiency improvements gain increasing importance as this industry looks to accommodate increased pumping loads, to improve the reliability of existing units, and to lower the accelerating cost of maintenance for existing equipment.

According to discussions with engineering and vendor firms, it is estimated that the potential market for new compressor drivers purchased/installed within the U.S. could range between 50 and 100 annually, as the industry acts to repower existing compressor stations to gain efficiency improvements to remain competitive. The driving force for this need is that wellhead gas prices are rising faster than the price of gas delivered to the user (see Appendix A of Topical Report No. 5)

#### 5.3.3.2 Trends in the Oil Production Industry

The U.S. petroleum pipeline network encompasses over 204,000 miles of transmission pipeline, and over 108,000 miles of crude oil pipelines carrying domestic and crude oil from producing fields and ports to refineries. In addition, there are over 72,000 miles of refined-product lines moving gasoline and other products to market, and over 23,000 miles of LPG lines transporting commodities such as propane and ethane. There have been shifts within the industry, and crude oil pipeline mileage has declined while product pipeline has increased.

There appears to be enough domestic crude oil pipeline capacity for the next 10 to 20 years, and there are no major logistical problems anticipated. Some additions may be made in order to remove bottlenecks and improve flow as supply and demand changes occur.

#### 5.3.3.3 Common Trends in Oil and Gas Industries

The U.S. oil and gas industries are not expected to open any significant numbers of new oil fields, nor are they expected to make any large investments in opening up new natural gas fields. However, it is expected that the industry as a whole will be taking a look at the possibilities within the newly-deregulated electric power generation field, offering alternative sources of fuel to non-utility markets.

Pipeline companies and local distribution companies are expected to become more involved in electric power generation as the electric industry becomes increasingly more competitive and it becomes easier for new competitors to enter the market. This trend will also feel the effects of attempts to further reduce operating costs through self-generation of power

The U.S. pipeline industry is significantly affected by the issue of environmental compliance. Regulations regarding exhaust emissions (primarily NOx) and noise are making environmental compliance a major problem for the industry, since current technology solutions are limited.

The primary factors affecting the selection of driver technology appear to be the same for both the oil and natural gas industry. Major purchase factors affecting purchase decisions include: capital cost, environmental performance, operating costs, efficiency and siting. Of these factors, the major issues are capital cost and environmental performance.

### 5.3.4 Trends in Cogeneration

Cogeneration is used by many industries, typically in the form of steam, for various manufacturing processes. Most industrial plants produce their steam or thermal energy requirements in a boiler and separately purchase their electric power from the electric utility grid. An industrial facility using cogeneration produces both steam and electrical energy using the same primary energy input.

The decrease in the cost of electricity in the first half of this century led to a decrease in retail cogeneration. However, a number of emerging factors, most notably industrial sited distributed generation, could lead to a resurgence in retail cogeneration in the late 1990's.

The three dominant cogeneration user groups (paper, chemical, and refining) represent 52% of the capacity in the 1-40 MW size range. Other very significant market sectors include agricultural and food, other industrial, and commercial/institutional facilities. The "other industrial" category consists of lumber, fabrication manufacturing, district heating, and water-to-energy plants.

Deregulation is the source of the trend favoring consideration of cogeneration by many industries and other potential users.

### 5.3.5 Trends in the Commercial Segment

Multi-building commercial facilities with central physical plants represent potential opportunities for cogeneration, and for prime mover driven cooling equipment. Steam uses for recovered exhaust heat include space heating, domestic hot water and absorption cooling.

Electric rate structures are shifting an ever-increasing share of the cost of electricity to the peak user, driving up the operating cost of conventional electric cooling. Furthermore, the aging stock of central plant HVAC equipment, coupled with mandated phase out of CFC's will drive an unprecedented chiller replacement market beginning in the mid 1990's. This window of opportunity for gas turbine driven chiller equipment should last for about ten years, into the year 2005.

## 5.4 ATS MARKET POTENTIAL

Energy consumption, both natural gas and electricity, is closely related to the level of activity within a country such as that measusred by gross domestic product (GDP). Further Solar has found that sales of industrial gas turbines to its dominant customer, the oil and gas production industry, closely matches natural gas consumption. Accordingly, three energy use predictions and three energy economic scenarios provided the basis for market projects. Information from three organizations was used to construct these scenarios: the American Gas Association (AGA), the Gas Research Institute (GRI) and the Department of Energy's Energy Information Administration (EIA). Although each organization's forecast generally rely on the same historical data, the individual forecasts differ dramatically along several dimensions important to the ATS market potential. The scenarios are presented in Tables 8 and 9 from the report by RDC that forms Appendix A in Topical Report No. 5. The latter should be consulted for details relating to these data.

**Table 8. Summary of U.S. Primary Energy Use by Scenario (Quadrillion Btu)**

| | 1995 | | | 2000 | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | Natural Gas | Electricity | Total | Natural Gas | Electricity | Total | Natural Gas | Electricity | Total |
| AGA TERA | 22.0 | 34.9 | 89.6 | 23.6 | 37.6 | 91.4 | 26.1 | 39.9 | 95.6 |
| GRI Baseline | 21.0 | 32.6 | 88.6 | 22.8 | 34.8 | 93.1 | 26.0 | 41.9 | 103.3 |
| EIA Reference | NA | NA | NA | 22.7 | 34.3 | 95.7 | 24.9 | 37.7 | 105.2 |

**Table 9. Basic U.S. Economic and Energy Scenario Parameters**

| | GDP Price Deflator (%/yr) | | | Crude Oil [Refiners Acquisition] ($/barrel) | | | Natural Gas [Field Acquisition] ($/Mcf) | | |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | 95-00 | 01-05 | 06-10 | 1995 | 2000 | 2010 | 1995 | 2000 | 2010 |
| AGA TERA | 4.0% | 4.4% | 4.6% | 17.65 | 22.00 | 25.00 | 2.30 | 2.65 | 3.15 |
| GRI Baseline | 2.7% | 2.0% | 2.0% | 19.99 | 21.69 | 27.88 | 2.14 | 2.56 | 3.19 |
| EIA Reference | 2.6% | 3.3% | 3.5% | NA | 21.34 | 29.00 | NA | 2.49 | 2.98 |

The fuel price projections for the three scenarios show a marked difference. For the period 1992 to 2010, the projections are for an increase of 67, 86 and 67% respectively in the wellhead price (in constant dollars), but for smaller increases ranging from 22 to 61% for the increase in the price of gas to industrial users. The EIA scenario with the highest percentage increase in the price of gas supplied to utilities (79%) shows a rise in industrial electricity prices of +8.3% whereas the other forecasts give a decrease in cost of both electricity and gas supplied to utilities.

In spite of the large differences in the prices estimated in the scenarios from the three different sources, the relationship between the price increases are the same. For example, the EIA scenario showed greater increases in the prices of electricity and gas, but the ratio remained the same. Hence, the competitive positions of utility generated electricity and distributed power generated by ATS units remains essentially the same independent of the scenario. Table 10 presents the market forecast for both domestic and foreign markets.

The foreign markets are extremely important. Solar is the major international supplier of industrial gas turbines in the range 1-20MW and relies on the large volume of exports to achieve lower prices per unit. In addition, the foreign markets are beneficial to the balance of trade of the United States. Similarly, the energy savings worldwide are important from conservation and global warming reduction.

**Table 10. Industrial ATS Market Summary for the Period 2000-2010**

| Industrial ATS Market | U.S. Markets | Foreign Markets | Market Totals |
|---|---|---|---|
| **Total Installed Capacity:** | | | |
| Oil & Gas (khp) | 1,702 | 10,734 | 12,436 |
| Electric Power (MW) | 8,192 | 4,821 | 13,013 |
| **Total Capacity (MW)** | **9,460** | **12,818** | **22,278** |
| **Cumulative Energy Savings:** | | | |
| Oil & Gas (trillion Btu) | 26 | 111 | 137 |
| Electric Power (trillion Btu) | 203 | 93 | 296 |
| **Total Energy Savings (trillion Btu)** | **229** | **204** | **433** |

The oil and gas forecasts reflect the movement of international oil and gas companies to overseas operations. The figures represent shipments of nearly 200 of the 5MW ATS units per year for the oil and gas industry. The electric power forecasts reflect growth of distributed power in the United States with considerable foreign shipments for a total of an average of 260 of the 5MW ATS units per year.

## 5.5 RISK ANALYSIS

During the course of the market survey, several issues were raised reflecting the risk that the market potential would not be reached. These issues included:

(1) Need to achieve cost and performance targets.

(2) Achieve less than 8 ppm NOx over 50-100% load.

(3) Demonstrate remote operation.

(4) Demonstrate ability to produce high quality electricity.

(5) Provide convincing field demonstration(s).

(6) Recognize contrasting needs of two principal markets.

(7) Take advantage of Solar's exceptional reputation and unique market position in world-wide oil and gas to build presence and image in field of distributed power as market emerges from deregulation.

(8) Continue to maintain lead over emerging technologies of fuel cells and photovoltaics.

# Section 6

# SYSTEM DEFINITION AND ANALYSIS

This work constituted WBS 2.6 on the ATS Program. Topical Report No.6 should be consulted for details of this work.

## 6.1 INTRODUCTION

This definition of the ATS describes the system design and analysis of the gas turbine, power plant equipment, and balance-of-plant equipment. The section explains how advanced features of the system components will achieve program goals. It also contains estimates of cost, performance, emissions and RAMD, and the advanced systems used to achieve estimated RAMD goals.

- Energy conservation: Thermal efficiency 15% 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% lower than with current systems.
- Reliability: Reliability, Availability, Maintainability and Durability (RAMD) better than with current systems.

The proposed ATS must be capable of completing development, including a field evaluation, and be ready for commercial introduction by the year 2000.

Topical Report No. 6 should be consulted for details of these requirements including references to the sources of specific statements.

## 6.2 SYSTEM SELECTION

The requirement that the selected system be ready for commercial acceptance by the year 2000 has provided important guidance for this program. It has been the basis on which Solar has selected a system for introduction by the year 2000 that meets the four goals defined by DOE yet does not achieve the longer range goal set by Solar. The plan introduced by DOE in this Phase II to design and test critical technologies (see Section 7 for the 9 critical technologies) will assure achievement of the longer range goals by a later date to be defined partially by the marketplace. A continual interplay between the market (see Market Survey, Section 5) and the system requirements (Section 3 and this section) is a characteristic of this program. Such interplay introduces a dynamic and iterative character to the program between "technology pull" and market acceptance.

At the present time based on the work in Section 3, "Selection of Cycle to Meet Market Needs", the options to be developed are:

| | 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 meet the program goals, as defined earlier, but option A represents too large a step to attain by the year 2000. The lower pressure ratio machine represented by option B will be introduced by that date. Option B will deliver significant ATS benefits – lower cost of power, cleaner air, fuel conservation, U.S. jobs and export dollars – within the resources that Solar and DOE can assign to the development.

An important step in the evolution of this strategy was the discovery that an optimized recuperated cycle could attain thermal efficiency levels in the neighborhood of 45% – well along the path from today's 34% simple cycle gas turbines to the ICR's 50%. An "optimized" recuperated gas turbine is defined as one in which the entire system, including the core engine, is designed for operation in a recuperated cycle. Nearly all recuperated gas turbine systems in operation today are a result of adding a recuperator to an existing simple cycle design. Unless extensive changes are made to the core engine, this practice results in substantial compromises to thermal efficiency, cost and RAMD factors.

Other considerations leading to this decision have been presented in Sections 3 and 5; reference should be made to these or to the detailed Topical Reports with the same numbers for more details backing the adopted strategy.

### 6.3 CONCEPTUAL DESIGN OF RECUPERATED ENGINE

The proposed layout for the recuperated cycle ATS design is shown in Figure 7. 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.

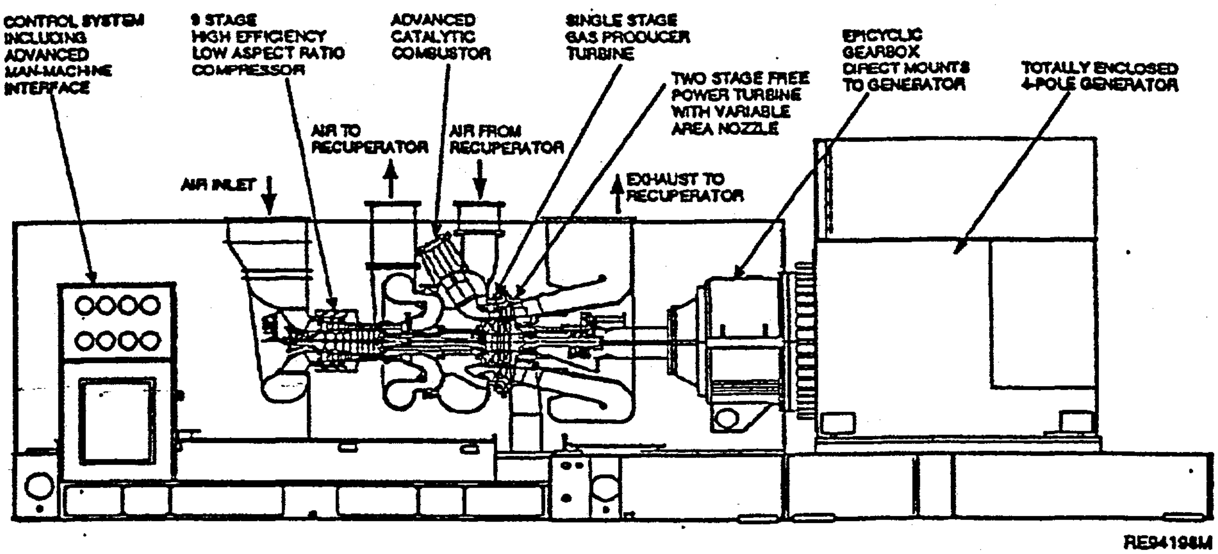



**Figure 7. Solar's Advanced Turbine System (Cross-Section)**

Marketing studies reported in Section 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.

The scaling laws used are described and discussed in the Topical Report.

An important consideration in selection of Option B was the reduction of risk. One way in which this arises is that only one-half point of thermal efficiency is lost by the selected firing temperature of 1180°C (2150°F) TRIT but this allows use of the well-proven Type 347 stainless steel recuperator in the event that advanced recuperator material development is delayed in development (see Sections 7.1 and 7.7).

Risk is reduced further in the case of bearings. 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.

## 6.4 CYCLE ANALYSIS

A key step in development of an engine configuration is the generation of performance parameters for each configuration and cycle point. From these, a model is developed which can be used to calculate the performance of an engine through operating parameters such as output power, fuel flow required, temperatures and pressures throughout the engine, etc. This model is developed by obtaining performance data for all of the individual components in the engine, the engine configuration, and cycle point at which the engine operates.

A cycle point is the combination of engine design point parameters which can be changed (overall pressure ratio, turbine inlet temperature (TIT), etc.), resulting in changes in the engine performance (thermal efficiency, output power, etc.) for a given configuration, or arrangement of components, there will be one or more combinations of these variable parameters (cycle points) which will give a maximum or minimum of some engine performance parameter.

Given all of the required component performance information, and the configuration and cycle point, a model of the engine can be constructed. By determining how the component performance changes with changes in cycle points, the performance of many different cycle points can be determined for a given engine configuration. The process can then be used to determine which cycle point most closely meets a given criterion (thermal efficiency, for example) for a given engine configuration. Studies of this type are defined as design parametrics.

### 6.4.1 Design Parametrics Matrix

A design parametric is carried out by evaluating a large number of combinations of cycle parameters which influence the overall performance, to determine which combination most closely meets the requirements. These points are called a matrix, because they usually include varying several parameters such that a set of values for one parameter is executed for each value in a set for the other parameter. For the ATS program, the parameters of most interest were turbine rotor inlet temperature (TRIT) and overall pressure ratio.

In a design parametric, many different cycle points are evaluated for each engine configuration under consideration, to determine those most closely meeting the goals. However, to be able to run each of these cycle points, the value of all of the component performance parameters (such as component efficiencies, pressure losses, cooling flows, etc.), must be known at each point. Obviously, complete designs of all components for a large matrix cannot be done.

Therefore, the study is executed by generating predictions of where the optimum cycle should lie for each engine configuration, and calculating designs on five points in the area of the optimum. The first point is the estimated optimum cycle point. The next two points are points at lower and higher pressure ratios, with the same firing temperature. And the last two points are at lower and higher firing temperature at the same pressure ratio. This combination of points is then used to interpolate and extrapolate the value of all other points in the matrix. At least 23 analytical models were use din this parametric work ranging from the standard ANSYS and TASCFLOW (3D viscous flow) to in-house developed codes to describe specific component performance and component interactions. Topical Report No. 6 gives full details of these.

### 6.4.2 Input Values

The engine parameters such as component efficiencies, pressure losses and cooling flows for each cycle point can be broken down into two categories. The first category consists of the parameters whose values exhibit negligible change with overall pressure ratio and turbine rotor inlet temperature (TRIT). These values include the intercooler, recuperator and combustor parameters.

The second set of parameters are those which vary as a function of the overall pressure ratio and TRIT of the cycle. These parameters were determined by performing preliminary component designs at the selected cycle points, and interpolating and extrapolating these values to determine the values to be used at the other overall pressure ratio and TRIT combinations in the study. Parameters under evaluation include compressor and turbine efficiencies, inter-turbine pressure losses, and turbine cooling flows.

### 6.4.3 Preliminary Design Iteration

Preliminary design of the components involved iterative refinement of the designs by compressor and turbine aerodynamic designers, cooling flow designers, and mechanical designers. At each iteration, the compressor and turbine designs result in efficiency, pressure loss, and cooling flow information which was used to determine the cycle performance. This new cycle performance was used to refine the component design in the next iteration. The process was considered complete when the changes in the design resulting from the changes in the cycle performance become small enough to have negligible effect.

Initial aerodynamic designs were completed for the compressors and turbines. These involved interaction between the compressor and turbine designers to determine the best speeds for the components for each of the cycles. Once the turbine designs were completed, they were reviewed by the heat transfer and mechanical designers to make sure the designs were acceptable. The resulting designs were then used in cycle analysis, which in turn were used in the following phase of the component design process.

As a result of the design study, the optimum efficiency for a recuperative cycle, based upon technology consistent with the program time frame occurs between PR's (pressure ratios) of 7.5:1 to 8.9:1 and TRIT'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 TRIT, 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 11. The highest overall thermal efficiency is *not* achieved at the highest TRIT in the range, but by the configuration that most efficiently uses the range of material, cooling, cycle, and mechanical design options available.

**Table 11. Range of TRIT, Cooling and Efficiency at Selected PR for Solar's ATS**

| Configuration | TRIT °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

Table 11 shows the limiting component to be the Type 347 SS recuperator. Hence, this design iteration provides another useful purpose in ATS development and this is to determine the importance of this component upgrade in the overall planning. Similarly, the advantage of ceramic components to reduce the cooling air flows and raise efficiency is made clear. Sections 7.1 and 7.7 of this report address the recuperator limitation. The companion CSGT program as well as Sections 7.8 and 7.9 addresses the issue of ceramics.

## 6.5 ATS COMPRESSOR DESIGN

The ATS compressor (Figure 8) will be scaled directly from several stages of the Solar Advanced Component Efficiency (ACE) compressor. The ACE compressor is a 15-stage axial design with a pressure ratio of up to 20:1 and adiabatic efficiency of 87.6%. 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).

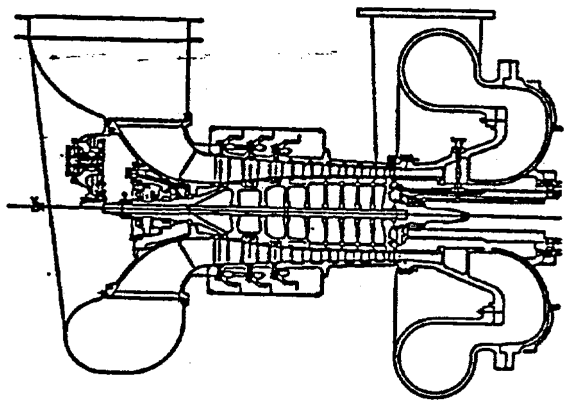


**Figure 8. ATS Compressor**

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 12 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.

The compressor flowpath and aero design parameters were determined in this Solar-funded development using a proprietary axial compressor meanline performance prediction program. The program was used to determine the performance impact, stall margin and efficiency, of the following parameters:

- Rotational speed
- Number of stages
- Stagewise aero loading distributions
- Flowpath definition (flow areas, hub/tip radius ratios shape (i.e. constant tip, hub or mean radius), length
- Blading aspect ratios
- Blading solidity levels

**Table 12. 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 (%) | 88.5 | 86.0 |
| Corrected Rotational Speed (rpm) | 19,244 | 15,000 |
| Number of Stages | 9 | 12 |

## 6.6 RECUPERATOR

A comparative study of recuperator types was made and is presented in Table 13. The Solar PSR was selected for ATS.

**Table 13. Comparison of Recuperator Types**

| 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. | | | | |

The data for Solar's Prime Surface Recuperator (PSR) is derived from nearly 2 million hours of field operation including operation on non-Solar gas turbines such as General Electric's Frame 3. Details of this recuperator can be found in Section 7.1.

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.

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's current PSR recuperator technology meets ATS design goals but innovative uses of alternate materials will further increase the recuperator's life in preparation for future thermal uprates. The thermal uprate vision is one of the main reasons why Solar is committed to recuperator development described in Section 7.7.

The Solar ATS cycle has a pressure ratio of 8.9 and a recuperator gas inlet temperature of 631°C (1168°F). The recuperator has a life of more than 100,000 hours at these conditions when constructed of SS 347. When higher firing temperatures can be justified from a cost/performance standpoint (due to advances in hot section technology), the recuperator inlet temperature would increase, reducing its life. Also, part load operation with a variable area nozzle (VAN) can increase the exhaust temperature by as much as 38°C (100°F). It is this temperature growth scenario that provides the impetus for qualifying a modified stainless steel type (e.g., SS 310) and other higher performance recuperator materials currently being evaluated (see Section 7.7).

Performance prediction is a critical issue in evaluation of the overall ATS performance. Section 7.1 gives an example of prediction of thermal effectiveness. The parameter of pressure drop is equally important and an example of correlation between computer codes and test data is given in Figure 9.

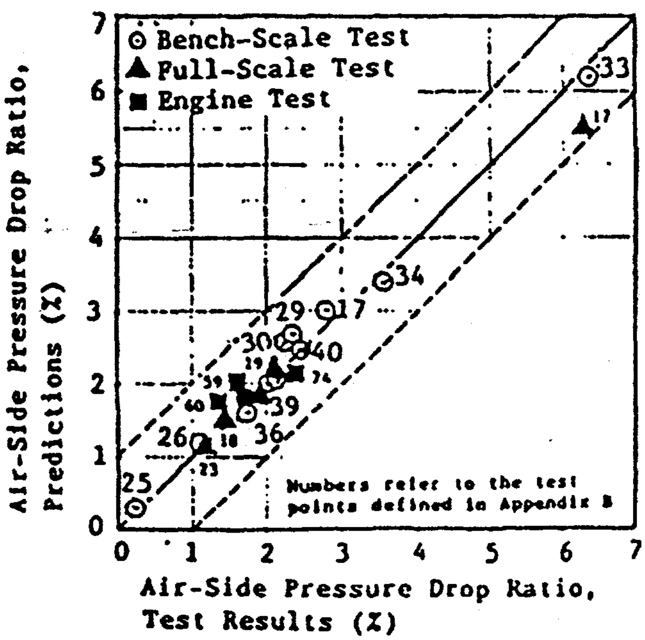



**Figure 9. Pressure Drop Ratio Correlation Comparison Between Predicted and Measured Air-Side Pressure Drop for the PSR Recuperator (M1 Configuration)**

## 6.7 COMBUSTOR DESIGN

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. One approach to low NOx emissions is to reduce the combustor primary zone equivalence ratio ($\phi$), and hence, 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 10. 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.

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 14. 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.

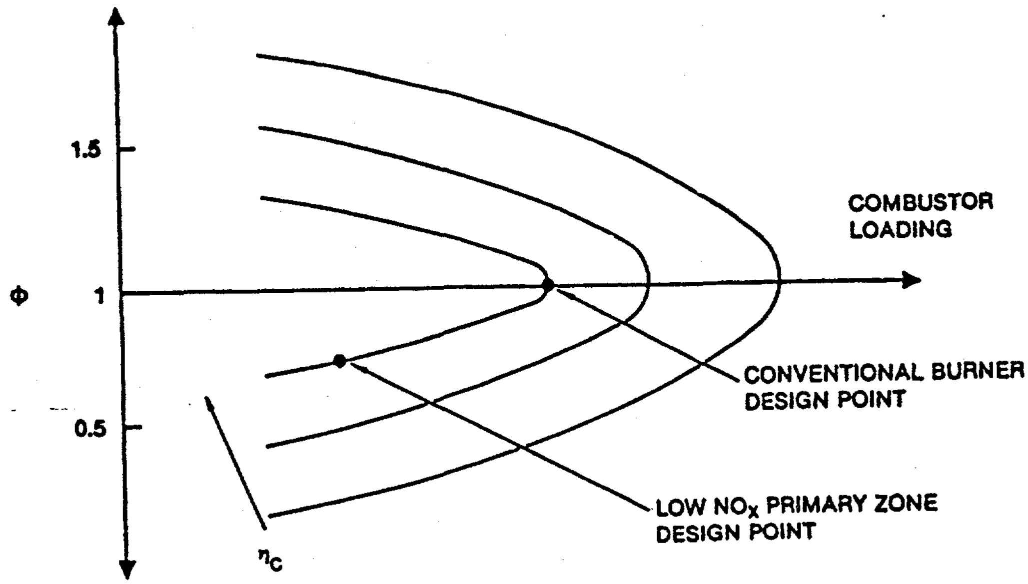



**Figure 10. Representative Combustor Performance Map**

**Table 14. 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% |

Technology development for the catalytic combustor is presented in Section 7.2 with scale-up work presented in Section 7.5. A schematic showing integration of the can-annular combustor is shown in Figure 11.

As a backup to the catalytic combustor (Figure 11), development, an ULP system will be developed in parallel 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. Both types of combustor will be discussed.

### 6.7.1 Catalytic Combustor

A preliminary catalytic combustor design for the ATS engine was completed during Phase II. The baseline design was for an approximate 12 MWe ICR machine with 12:1 PR, 655°C (1212°F) T2, and a 1343°C (2450°F) firing temperature. At these conditions a eight can, can-annular approach

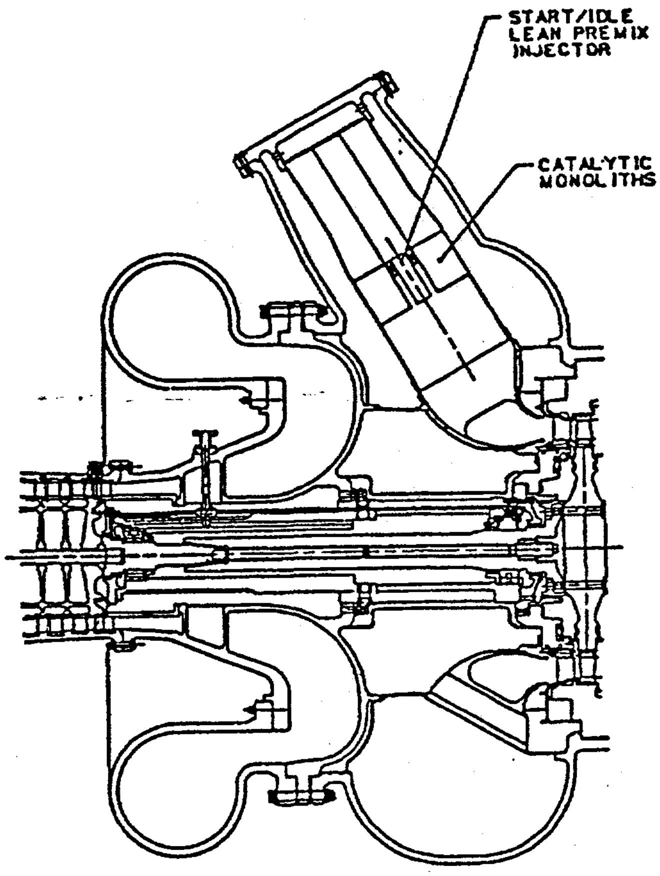



**Figure 11. Engine Cross-Section Showing Can-Annular Catalytic Combustor for ATS Gas Turbine**

was selected as the primary design as shown in Figure 11. Each can has a catalyst flow path diameter of 10 inches. Along the center-line of each can is a 11.4 cm (4.5 inches) diameter part load lean-premixed injector that ends at the exit of the catalyst bed.

Catalyst inlet conditions have been defined and provided by Engelhard Corporation of Catalytica, the catalyst suppliers. These are a 1764 cm/sec (60 fps) face velocity, 426°C (800°F) minimum inlet temperature, and a 3.5% to 4% fuel-air ratio by volume. Using the catalyst inlet conditions as a starting point the overall fuel-air ratio is calculated so that the combustor provides the required temper-ature rise. The adiabatic flame temperature is calculated with the STANJAN code or the NASA temperature rise curves for natural gas NASA TP-2435. These calculations are com-pleted at 0, 50, and 100% load.

Development of the catalytic combustor technology during Phase II is described in Section 7.2.

From the point-of-view of design, it should be noted that the catalytic combustor will require more complexity than conventional combustors. A variable geometry system (modulating inlet control valve) regulates air flow between the part-load injector and the catalytic reactor. Since gas temperatures are below 649°C (1200°F), the part-load system needs no exotic materials.

In operation, the part-load injector fires from engine light-off up to 50% power. At 50 percent load the inlet valve begins to close as air and fuel flow are diverted to the catalyst bed. The catalytic reactor operates from 50 to 100% load as the inlet valves control the air split between the catalytic reactor, the part-load injector and the dilution zone.

### 6.7.2 Ultra-Lean Premixed (ULP) Combustor

The ULP combustion system (Figure 12) will build upon Solar's lean premixed combustion technology (SoLoNOx) that was recently introduced to the gas turbine market (Figure 13). 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.

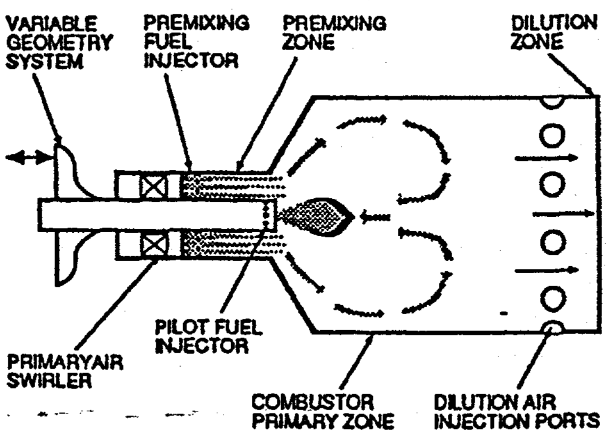
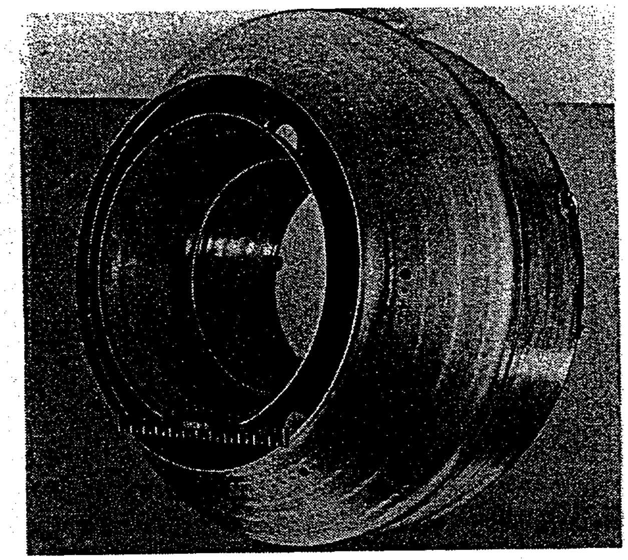



**Figure 12. ATS Ultra Lean Premixed Combustor Approach**



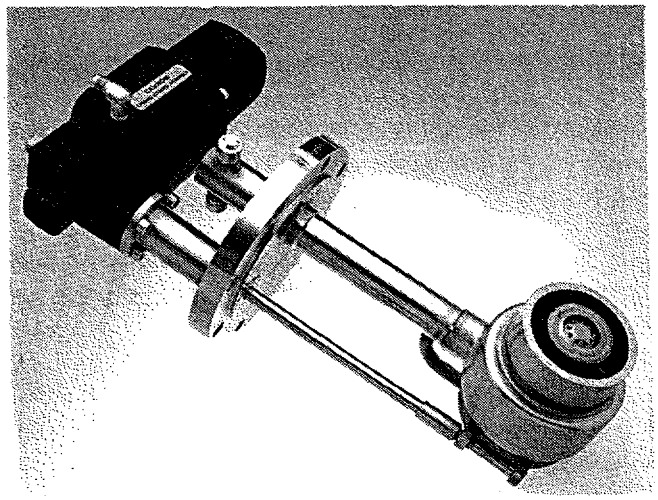


**Figure 13. SoLoNOx Combustor Liner (top) and Fuel Injector (bottom)**

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.

The fuel injector module includes a primary air swirler, premixing fuel injection tubes, and a pilot fuel injector. Two methods of fuel injection provide adequate combustor operating range. The premixing fuel injection tubes are used when the combustor operates in the low emissions mode. These are a series of multi-orificed radial fuel tubes that inject natural gas into the premixing channel downstream of the air swirler. The fuel and primary air mix in the swirler channel prior to reaching the combustor primary zone. For lightoff and low load operation, a pilot fuel injector has been incorporated in the fuel injector module. This injector is more conventional in design, delivering fuel directly into the primary zone. This enhances combustor stability compared to premixed injection.

Sizing of the ultra-lean premixed combustor was accomplished by scaling from a combustor performance database accumulated through a series of rig tests employing natural gas-fired, lean premixed burner primary zones. The database reflects only atmospheric pressure testing. Thus the extrapolation to higher pressures requires assumptions as to the variation of pressure on NOx emissions and attainable combustor loading.

An analysis of the lean-premixed burner database indicates that over the range of parameters tested, NOx emissions are primarily dependent on primary zone equivalence ratio and not on combustor loading. This is illustrated in Figure 14 which shows typical NOx emissions data plotted against the ratio of combustor volume to air flow rate ($V_c/W_a$).

Corresponding CO emissions test data shows that at fixed equivalence ratio, CO emissions increase as combustor loading increases. This led to a method to make a preliminary sizing of an ultra-low NOx primary zone.

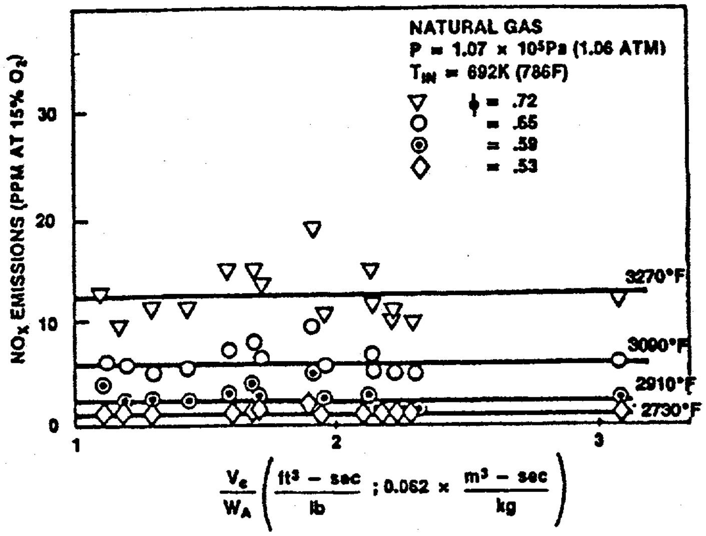



**Figure 14. Effect of Combustor Loading on Lean Premixed Burner NOx Emissions**

### 6.7.3 Fuel Flexibility

Section 4 discuses the possible future need to operate an ATS on alternate fuels. Firing by gasification products is feasible but small gasification plants do not appear to be practical from an economic viewpoint. A central gasification plant providing gas to several users may be possible. Further discussion of this issue can be found in Topical Reports 4 and 6.

## 6.8 ATS TURBINE DESIGN

### 6.8.1 Technical Challenges – Gas Producer Turbine

The design challenge associated with the ATS turbine was 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 lack 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 TRIT, 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 TRIT. 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 TRIT, 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.

Another illustration of the technical challenge is provided in Table 15 where ATS is compared with the industry baseline provided by the recently introduced Taurus 60.

**Table 15. 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 gas producer turbine will be a clean sheet design using the latest aerodynamic design techniques to achieve the goals in Table 15. The decision to use a single stage, high work, low aspect ratio blade was made for these reasons: (1) single stage uses less cooling air than two stages; (2) reduce cost; and (3) the efficiency penalty was less than that associated with a two stage turbine requiring more cooling air. Details of the design considerations are given in Topical report No. 6 including the selected turbine design points.

### 6.8.2 Technical Challenges – 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 16. This Table contains a comparison of the ATS to the industry baseline and indicates the performance advantages of the ATS turbine over the traditional Solar industrial turbine. The two lightly loaded stages in the PT 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 15, provides a means to accomplish these goals, albeit with a small efficiency penalty due to compromises in flowpath geometry.

There is a significantly shorter transition duct between the GP and the PT, representing an alternative to an equivalent duct of significant area ratio and increased length requiring structural support.

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

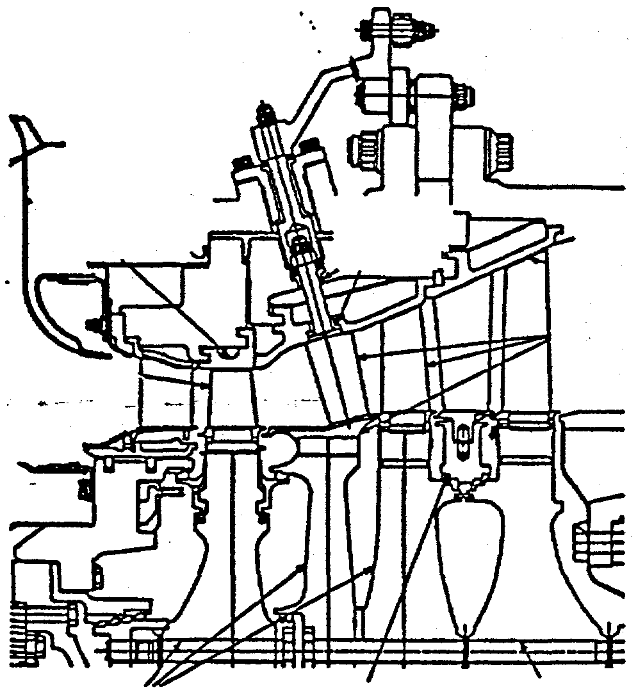


**Figure 15. ATS Turbine Configuration Showing 'Close-Coupled' GP to PT Transition Duct**

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.

Figure 15 shows that the first nozzle of the power turbine is variable to allow for better off-design performance by maintaining a constant TRIT, 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.

The diffuser was sized for optimum recovery with the area ratio and length of the diffuser. 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.

**Table 16. 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 |

### 6.8.3 Turbine Blade Tip Clearance Control

Turbine tip clearance is one of the most important sources of loss of efficiency in a turbine. For example, the lack of reliable technology to permit a blade tip rub against a seal is a major source of efficiency loss in the companion CSGT program. Factors that need to be considered that affect this problem, particularly in the case of unshrouded blades are:

- Differences in thermal radial growth between the turbine rotor assembly and nozzle tip shroud support structure during transients. This is usually the most severe during hot restarts, when tip clearances are drastically reduced due to more rapid cooling of the stator than of the rotor.

- Relative axial rotor-to-stator thermal displacements with non-cylindrical blade tips.

- Circumferential thermal distortion of the tip shroud support structure resulting from non-uniform combustor exit temperatures during transient or steady-state operation.

- "Bowing" of tip shroud segments during transients due to through-wall temperature gradients.

The turbine static structure plays a dominant role in turbine clearance control and in positioning the nozzle shrouds over the blade tips. Solar has developed a semiactive tip clearance control technique that modulates cooling air (shuts it off) during start and shutdown cycles. This allows the stationary structure to heat up and grow away from the rotor during transients, avoiding blade tip rubs and minimizing tip clearances during steady state operation.

Aircraft engine manufacturers often reduce tip clearances by continuously modulating cooling flow to the stationary components, as they need active systems that respond rapidly to thermal transients. Industrial engines do not require this degree of complexity; tip clearance control is needed only for steady-state operation. The adverse RAMD and cost impacts associated with an aero engine approach make it unsuitable for industrial engines.

## 6.9 TOTAL PLANT CONTROLS

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 are much lower than at the job site. Delivery, installation, and start-up are much faster.

An uninteruptable AC power supply (UPS) will be used to protect those essential services on the GFATS 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 utilizes valve-regulated, gas-recombination cells. Battery cells will be made of lead calcium which can be recycled.

Section 7.6 of this report gives more details. A full account of this work is provided in Topical Report 8.6.

## 6.10 OVERALL SYSTEM

The overall system is shown in Figure 16 together with critical features and the advantages or trade-off that led to those choices.

CONTROLS AND ELECTRICAL

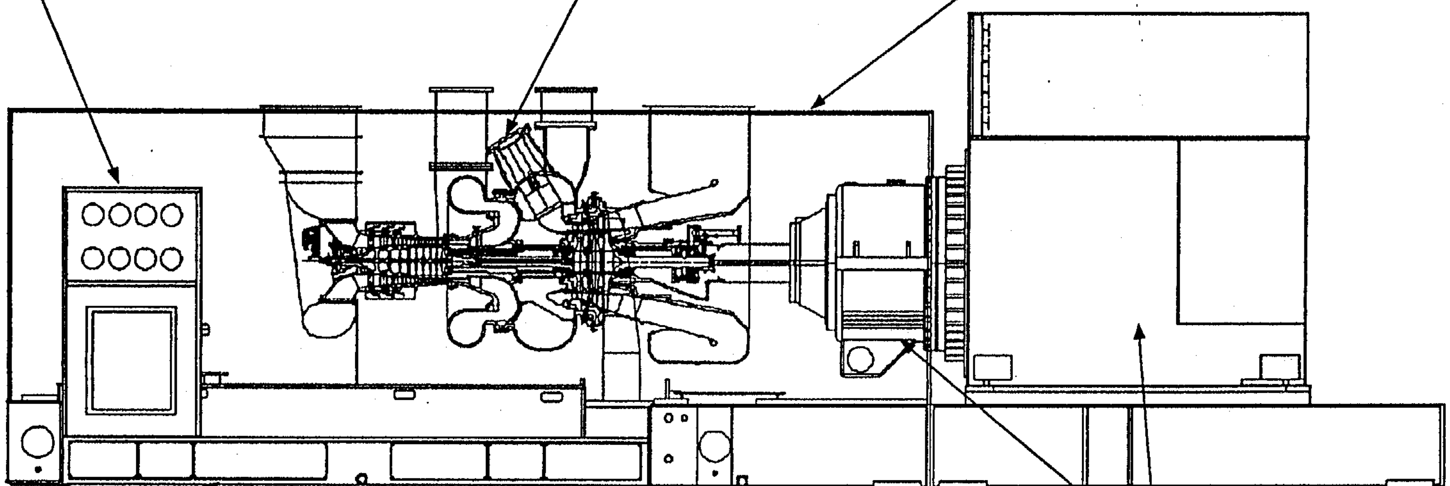
- Advanced MMI and control system for improved RAMD, reduced cost of power.
  - Remote Operation
  - Plant Load Management
  - Built-in Diagnostics
- On-skid controls for improved RAMD, reduced cost of power.
  - Reduced Factory Wiring
  - Reduced Site Wiring
  - Simpler Commissioning
- Uninteruptible 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 sturctural 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 demistor located in vent to ensure removal of 99.9% of oil particles.
- Single cartridge type oil filters for up to 10,000 hours oil 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-lube, elimination of need for pressure relief, temperature control, system relief valves and associated piping and instrumentation.

DRIVEN EQUIPMENT

- Epicyclic reduction gearbox
  - Compact, straight-through 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 mimimum noise and parasitic losses.

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**Figure 16. ATS Subsystems and Features**

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 16 details the ATS subsystems and components and indicates their features and benefits. Figure 17 shows another view of the integrated package design giving more three dimensional detail to the air inlet duct, recuperator, and driven equipment.

### 6.10.1 ATS Driver Frame

The driver frame will encompass the turbine, start system, lube oil system, gas fuel system and on-board programmable logic controller. It will be constructed from carbon steel material, welded for structural integrity. The frame will use three-point mounting to simplify foundation design and site installation time. Integral lifting points will be incorporated to facilitate handling and site installation. Provisions to accommodate an acoustical enclosure will be incorporated for applications requiring noise attenuation. For environmental considerations, the frame design will be capable of containing oil spills and waste water resulting from routine maintenance of the equipment.

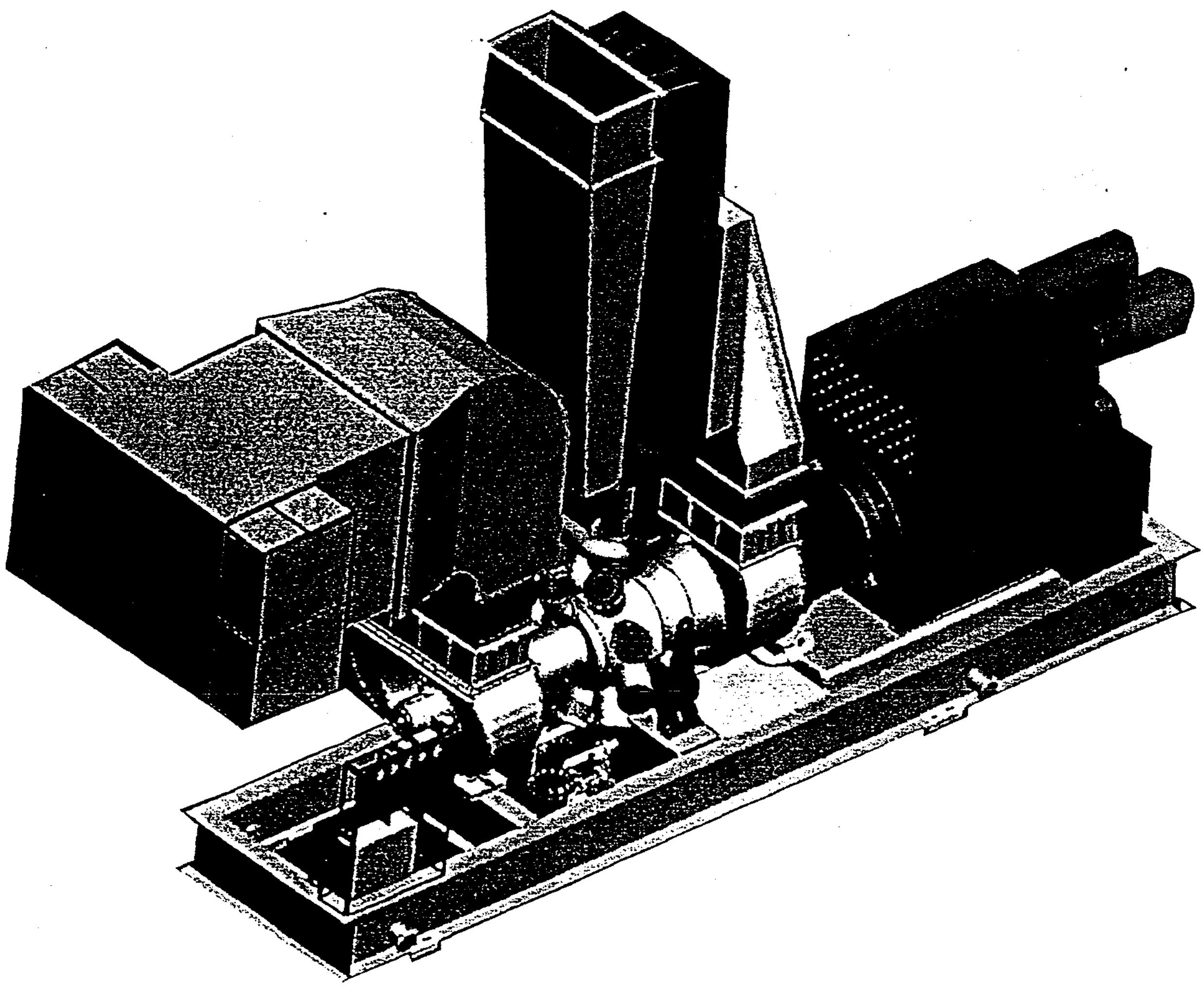

Figure 17. View of Integrated Design Package

The ATS will not use older style systems for starting such as pneumatic or hydraulic but will have a variable frequency controlled AC motor directly coupled to the front end of the turbine. A simple sprag type clutch will disengage the motor from the shaft at the appropriate speed.

### 6.10.2 Lube Oil System

It will consist of an oil storage tank, a variable frequency controlled AC motor driven positive displacement supply pump, an oil filter, an air-to-oil cooler with a variable frequency controlled AC motor driven fan, supply and drain piping, and control instrumentation.

Oil supply pressure and temperature will be maintained by independently regulating speed of the supply pump and the oil cooler fan by means of a variable frequency controller. Operating in this manner no longer requires using the traditional pressure control valve, temperature control valve and system relief valve. Higher reliability as well as reduced parasitic energy loss will be achieved by this change.

### 6.10.3 Condition Monitoring

One of the requirements to penetrate the market for distributed power (see Section 5) is remote condition monitoring and control. Power output will be monitored and controlled by the Total Plant Controls (Section 6.9 and 7.6 plus Topical Report No. 8.6). An important part of this control is in the lubrication system.

### 6.10.4 Fuel Gas System

The fuel gas system will consist of a primary "fire safe" isolation valve plus a secondary isolation valve. The secondary valve will also serve as a pressure control valve, regulating pressure to the turbine's fuel gas distribution manifold and fuel injectors. It will use an integral loop powered microprocessor controlled positioner providing accurate and responsive pressure control. It will replace an existing customized valve which is more costly, less flexible and less reliable. Again, higher reliability will be achieved for all markets.

### 6.10.5 Reduction Gearbox

The reduction gearbox will be an epicyclic star-gear design which will provide a compact straight through shaft arrangement avoiding the physical layout problems associated with designs using traditional offset shafts. Designed for continuous duty operation, the epicyclic gearbox has a minimum gear life of 100,000 hours; uses oil-filmed, forced-fed sleeve bearings with more than 100,000 hours of life; and only requires 30,000 hours between major inspections. The gearbox will be used to reduce output speed of the ATS turbine to the required operating speed of the AC generator, either 1500 rpm for 50 Hz service or 1800 rpm for 60 service.

### 6.10.6 AC Generator

The AC generator will be manufactured to the National Electrical Manufactures Association (NEMA) standards. Specifically, the generator will be a 4-pole design machine due to consideration for mechanical efficiency, size, weight and cost. It will be structurally capable of supporting the main reduction gearbox and being mounted directly to the same foundation as the driver frame.

Being a totally enclosed design, it can be mounted outdoors without any extra weather-proof/acoustical enclosure. An integral air-to-air heat exchanger, mounted above the generator, will provide proper cooling of generator insulation. Ambient cooling air will be passed through the heat exchanger by means of two AC motor driven fans. The speed of both fans will be controlled by a variable frequency controller to insure adequate cooling based on actual ambient temperature. Controlling fan speed will assist in minimizing noise emission and reducing AC parasitic losses.

#### 6.10.7 Package Enclosure

Provisions for an optional acoustical enclosure over the driver frame will be incorporated. When furnished, the enclosure will ship as an integral part of the driver frame. Panels can be removed to provide full access to facilitate either servicing or major repairs. The enclosure will include provisions for easy removal of the turbine, if necessary. Side panels will incorporate access doors allowing quick access into the enclosure for routine maintenance and simple repairs.

## 6.11 ATTAINMENT OF ATS PROGRAM GOALS

### 6.11.1 Pollution Prevention

Solar's experience as the world leader in industrial dry low NOx with over 116,000 hours of field operation provides a strong design platform for achieving ATS emission goals. Further, the new market identified in Section 6 in distributed power demands an ultra-low level of pollution in all fields: NOx; CO; UHC; and noise. Either the ultra-lean premix with ceramic (hot wall) combustor, or the catalytic combustor will meet the goals and give customers a choice. The silencing provided by the recuperator together with the acoustical enclosure (Section 6.10.7) will provide superior control of noise pollution reducing this to less than street traffic.

### 6.11.2 Reliability, Availability, Maintainability, Durability (RAMD)

Solar has installed an increasing number of remotely controlled units in recent years. An example of such an installation is a utility power station in the Northern Territories of Australia where three unattended 9 MW Solar units produce electricity for an entire community but are controlled from Darwin over 100 miles away. It is this background and experience that have allowed Solar to achieve high RAMD. Thus, the Gas Research Institute have estimated an availability of about 93% for all industrial gas turbine cogeneration systems whereas Solar's recent innovations in total plant design for operation and maintenance have achieved four year average availability levels of 97%.

Availability levels can only be achieved by total plant design and integration. This approach will be taken on the Solar ATS to achieve levels of 98%. The Solar ATS will be designed using techniques (QFD, NPI, industrial system component life criteria) that have been proven to produce a highly reliable and durable system. The choice of a moderate firing temperature cycle with matching materials of construction are critical in providing engine durability.

### 6.11.3 Cost of Power

The purchase decision for an industrial gas turbine system is strongly affected by system first cost. Less than 34 percent of typical system cost is accounted for by the core engine. Solar' design has taken a systems approach, making efforts to control all the components of first cost. This allows a modest ATS first cost increase relative to current comparable systems even though the ATS includes advanced pollution prevention technology. The total ATS cost of power (life cycle cost) will be considerably lower than that available with today's engines. The low first cost and high efficiency of the recuperated engine combine with Solar's highly reliable support systems to provide a balanced approach to minimizing the cost of power. The cost reduction will exceed 10% with the present price of fuel and will grow as fuel costs rise.

### 6.11.4 Thermal Efficiency

Solar's ATS design will achieve the high system efficiencies necessary to support the industrial user's needs through use of an advanced recuperator and innovative use of materials, achieving busbar efficiencies of 42-43% (45-45.5% at the turbine shaft). Recovering waste heat – whether through recuperators or via steam generators – has been continuously emphasized through Solar's gas turbine designs. This dedication to improved efficiency through waste heat recovery rather than through high turbine rotor inlet temperatures has made Solar a leader in the waste heat recovery field. Utilizing waste thermal energy recovery in a recuperative cycle will prove a more appropriate approach to providing high thermal efficiencies than using high firing temperatures in a simple cycle system.

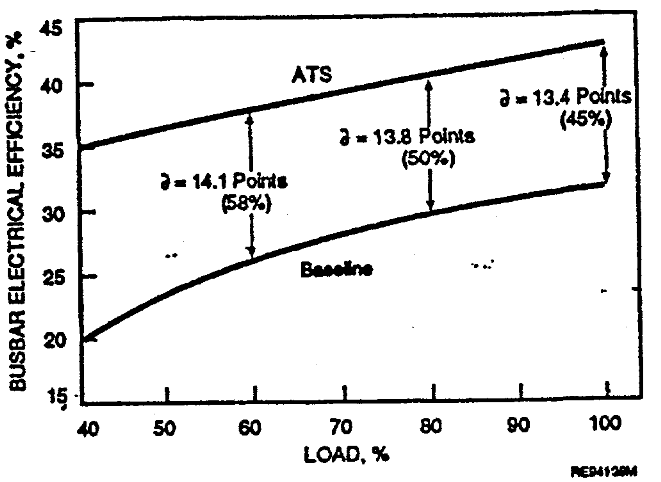


**Figure 18. Solar's ATS Electrical Efficiency as a Function of User Load**

An additional reason why the recuperated system has an advantage over a high firing temperature simple cycle machine is the retention of Higher Efficiency at Part Loads. Figure 18 shows that the busbar efficiency increase over the simple cycle baseline is 13.4 points at full load corresponding to a 45% increase. At 40% load, the increase is 15% but the increase is 75% over the efficiency of the simple cycle. These increases have been attained by detailed attention to parasitic losses. Figure 19 shows how these will be decreased by approximately 60%.

It will be noted that one of the largest para-sitic loses occurs in fuel gas compression. The optimum high temperature fired, simple cycle machine requires a high pressure ratio so that above 15:1 there will be a need for a complex and expensive fuel gas compression system.

### 6.11.5 Fuel Flexibility

This issue is discussed in Sections 4, 7.2 and 7.3 where approaches to be developed for ATS are described to provide fuel flexibility.

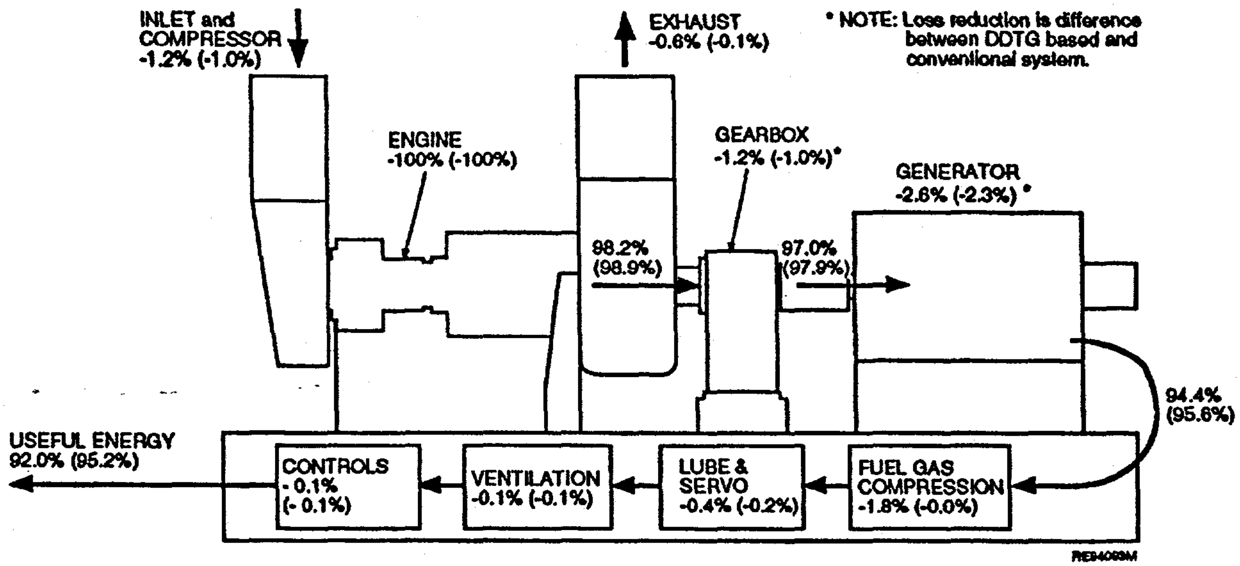


**Figure 19. ATS Parasitic Losses Showing Reduction From Typical Baseline Gas Turbine**