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**Advanced Turbine Systems Program
Conceptual Design and Product Development
Task 3 -- System Selection**

Topical Report

David J. White

July 1994

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

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

By
Solar Turbines, Incorporated
San Diego, California

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EXECUTIVE SUMMARY

Solar Turbines Incorporated has elected to pursue an intercooled and recuperated (ICR) gas turbine system to exceed the goals of the D.O.E. Advanced Turbine Systems (ATS) program. As defined by the D.O.E., the ATS goals are to develop and commercialize an industrial gas turbine system that operates at thermal efficiencies at least 15 percent higher than 1991 products, and with emissions not exceeding eight ppmv NO_x and 20 ppmv CO and UHC. Solar's goal is to develop a commercially viable industrial system (three-to-20 MW) driven by a gas turbine engine with a thermal efficiency of 50 percent (ATS50), with the flexibility to meet the differing operational requirements of various markets. The cycle selection was driven by system efficiency; reliability, availability, maintainability and durability (RAMD) considerations; system integration capability; and life-cycle cost reduction.

Dispersed power generation is currently considered to be the primary future target market for the ICR in the five- to-15 MW size class. The ICR integrated system approach provides an ideal candidate for the assumed dispersed power market, with its small footprint, easy transportability, and environmental friendliness. In comparison with other systems that use water or toxic chemicals such as ammonia for NO_x control, the ICR has no consumables other than fuel and air. The low pressure ratio of the gas turbine engine also is favorable in that less parasitic power is needed to pump the natural gas into the combustor than for simple-cycle machines.

Solar has narrowed the ICR configuration to two basic approaches, a one-spool, and a two-spool version of the ATS50. Both have advantages and disadvantages. For example, the one-spool engine will have a lower first-cost but lower part-power efficiencies than the two-spool version. The two-spool ATS may not only have better part-power efficiency, its efficiency will also be less sensitive to reduced TRIT levels. Thus hot-end parts life can be increased with only small sacrifices in efficiency. The flexibility of the two-spool arrangement in meeting customer needs is its major advantage over the one-spool. Further refinement of market requirements will largely decide the ICR configuration.

1. INTRODUCTION

1.1 OVERVIEW

This Task 3 Topical Report is intended to present Solar's preliminary system selection based upon the initial trade-off studies performed to date. Tasks 3, 5 and 6 are interactively related, because Solar's customers worldwide use both base-load power generation and part-load mechanical drive systems. The analysis undertaken in Task 3 has highlighted issues that need to be investigated as part of the Task 5 Market Study. Some examples of market-driven issues that affect the selection and design are:

- 1) part-load efficiency requirements,
- 2) water consumption, and
- 3) transportability.

Other market factors that impact the engine design are remote and/or unattended operation, and simplicity and robustness of the hardware. The results of the Market Study, in turn, will help refine the design definition as required in ATS Phase II Task 6 System Definition and Analysis.

This report refers to the ATS50. ATS50 is Solar's name for the Gas Fired Advanced Turbine System (GFATS) that achieves 50 percent engine thermal efficiency (at the shaft), as well as the other program goals specified by the U.S. Department of Energy (D.O.E.). The baseline ATS will meet the efficiency improvement goal of 15 percent, as well as the other requirements of eight parts-per-million (by volume) (ppmv) NO_x, and 20 ppmv CO and UHC. This designation and associated requirements were outlined in Solar's January 27, 1994 Phase III Rough Order of Magnitude (ROM) report to D.O.E. Solar plans to deliver two baseline ATS50s by the year 2000 for field testing. These first-generation systems will form the basis of the ATS50s, which then will have emerging technologies incorporated as they are developed. The first- and second-generation technologies are being developed in parallel and will be incorporated as the market requirements dictate.

1.2 REVIEW OF PHASE I - SYSTEM SCOPING AND FEASIBILITY STUDIES

A generic Advanced Turbine System (ATS) cycle was selected in Phase I of the ATS program. The cycle chosen as the most likely approach to meet both the efficiency and emission goals was the Ericsson Cycle. This cycle, as applied to a gas turbine, involves isothermal air compression, thermal recuperation and isothermal hot gas expansion. In general, true isothermal operation is impractical. However, isothermicity can be approached by adding on systems such as intercoolers and reheat combustors to a simple-cycle gas turbine. For example, intercooling between two adiabatic compressors can provide near isothermal compression, provided the pressure ratio of each compressor stage is low (about 4:1). Reheating between the gas producer turbine section and the power turbine section also can provide near isothermal expansion from a thermodynamic point of view. The intercooler and the recuperator (thermal recuperation) work together to maximize the recovery of otherwise wasted heat in the exhaust stream. This extracted energy is transferred to the air entering the combustor.

Analyses of a gas turbine so equipped show that an efficiency greater than 50 percent can be attained at pressure ratios on the order of 14:1-to-16:1, and with turbine rotor inlet temperatures (TRIT) of approximately 2450°F. The use of a reheat combustor was omitted from the primary

approach because of its complexity and the relatively small improvement in efficiency provided by its incorporation. At high pressure ratios with reheat between gas producer turbine stages the efficiency could be improved. However, the engine power density also increases, which reduces the engine core size significantly, and thus affects the compressor. Using this approach for small gas turbines (< 20 MW) creates a problem, in that the compressor blade sizes in the latter stages are so small, that the desired performance cannot be achieved. Additionally, emissions goals will be more difficult to achieve when reheat is employed.

To further improve thermal efficiency and emissions, an add-on system, chemical recuperation, was also studied. This system would extract thermal energy from the exhaust and convert part of it to fuel energy. The improved heating value and the clean-burning characteristics of the secondary fuel that is produced, would further reduce emission levels. The thermal energy redirected from the exhaust to the combustion system will, for a constant power output, improve efficiency. As with the reheat option, the chemical recuperation will be considered not necessary to meet the efficiency goals for ATS50, but it may be required to meet emissions goals and further improve efficiency. Chemical recuperation will be considered as a future enhancement to the ATS50.

The ICR approach provides an ideal candidate for the assumed dispersed market, with its small footprint, easy transportability, and environmental friendliness. In comparison with other systems that use water or toxic chemicals such as ammonia for NOx control, the ICR has no consumables other than fuel and air. The low pressure ratio of the engine also is favorable in that less parasitic power is needed to pump the natural gas into the combustor than for simple-cycle machines.

Solar has incorporated a primary surface-type recuperator (PSR) into the selected system. Solar and its parent company Caterpillar, Inc. have developed and refined PSR technologies over the past 16 years. The PSR is durable, reliable and delivers high performance in a compact size. Reduced noise emissions associated with PSRs in many cases have eliminated the need for exhaust silencers.

Solar's resulting selection is an intercooled, recuperated (ICR) gas turbine system. The balance of the Task 3 activity concentrated on the most appropriate configuration for the ICR gas turbine system cycle.

1.3 PHASE II - CONCEPTUAL DESIGN AND PRODUCT DEVELOPMENT

In ATS Phase II, Solar adopted a two-tier set of goals for its ATS product. Four Phase III goals in the following listing were adopted for the near-term ATS50 (year 2000):

- 1) 50 percent thermal efficiency (ATS50),
- 2) Eight parts-per-million (ppmv) NOx,
- 3) 10 percent reduction in the cost of power (COP), and
- 4) reliability, availability, maintainability and durability (RAMD) meeting (at least) today's standards.

For the far-term, beyond 2005, the efficiency and emissions goals selected were 60 percent thermal efficiency and five ppmv NOx. The same COP and RAMD as targeted for the first-generation ATS50 were retained. 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 as part of the Phase II Task 5 Market Study. The engine efficiencies given in this report are those at the engine design point (full power) at sea-level and a 59°F day, unless otherwise stated. The design point efficiencies quoted are sufficiently conservative that they should be close to the "guaranteed efficiencies", taking into account the estimated parasitic losses

The word "risk", where used in this document, is associated with technical risk unless otherwise stated. Risk, as used, 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. Incremental benefits will be involved (technical or market related) even if the component or process fails to meet the desired performance level.

Although the concept of RAMD as a primary driver for customer acceptance is valid, the issues associated with RAMD are not discussed in detail in this report. RAMD is primarily a function of the engine component and system designs. RAMD is considered in tradeoff studies from the start of the program, however, and are included in this document. The incorporation of features specifically intended to improve RAMD will be addressed in Task 6 System Definition and Analysis. Assessments of the likely overall ATS50 RAMD will also be provided as part of the output of Task 6.

A total of five candidate configurations of an ICR were evaluated in Task 3 (Selection of GFATS) of Phase II 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.

The five ICR configurations investigated are detailed in the sections below. The two engine configurations selected for further development from the five examined, include:

- 1) a one-spool gas producer section and a free power turbine and
- 2) a two-spool gas producer section and a free power turbine.

Advantages associated with the one-spool approach 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 will 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, 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 results of the Task 5 Market Study will allow Solar to make a selection that will maximize the commercial applications of the ATS. This decision point will occur toward the end of Task 6 System Definition and Analysis.

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.

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

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

The risk associated with the application of the Primary Technology Choice, the Back-up Technologies and the High-payoff Technologies varies within each area. 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. The technologies for each are listed in Table 1.

Table 1. Component Technology Selection Options

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

* 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. Field experience, combined with additional laboratory development, will assure ATS50 program goals can be met within the required time. 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 will consist of choices identified in Table 2.

Table 2. 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

In the event that demonstrator technologies are not available in the time frame required for the field evaluation systems, the back-up technologies from Table 1 would be selected.

2. SYSTEM SELECTION

2.1 OVERVIEW

The ICR gas turbine system chosen in Phase I can be configured in a number of 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. One of these configurations would place the power or free turbine as the first stage; another would locate the power turbine and the low pressure compressor on the same shaft; the third would use a flow split arrangement. This last approach would divide the flow after compression, with one stream going to the power turbine and the other to the gas producer turbines. Two recuperators and two combustors would be necessary to produce an ICR configuration with such a flow split.

All of these approaches were investigated in terms of their ability to meet the ATS50 program goals and also Solar's extended goals (Table 3). The performance of these five configurations was evaluated both on-design and off-design. 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.

While the above analyses were being performed, a more sophisticated performance code was under development. This 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.

Figure 1. One-Spool Gas Producer With Free Turbine

Figure 2. Conventional Two-Spool Gas Producer With Free Turbine

Table 3. Advanced Turbine System Goals

Parameter	Baseline ATS50 Goals	Expanded Goals
Thermal Efficiency	Fifty (50) percent	Sixty (60) percent
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)	Ten (10) percent Reduction From Today	Ten (10) percent Reduction From Today
Reliability, Availability, Maintainability & Durability (RAMD)	Equal To or Better Than Today	Equal To or Better Than Today

A more advanced cooling model was also developed 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 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, although the frequency of engine change-outs and associated downtime should be taken into account. This will be investigated during the Task 5 Market Study and Task 6 System Definition and Analysis.

2.2 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 (Figures 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 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 (Figure 3). By definition, fifty percent of the energy in the hot gas stream would be extracted by the power (or

Figure 3. Two-Spool Gas Producer With Power Extraction From the High Pressure Turbine

free) turbine when the overall thermal efficiency of the engine is 50 percent. Thus this turbine section potentially could provide the greatest temperature drop and, if positioned as the first turbine stage, could reduce the total cooling flow requirements. However, when this arrangement was investigated, 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. This added complexity and the cooling needs of the variable nozzle guide vanes would reduce the efficiency to a level approximately the same as that for the conventional two-spool configuration. Because the additional complexity would add cost and higher maintenance requirements with no significant efficiency advantage, this "power turbine first" approach was abandoned. A similar two-spool arrangement where the low pressure turbine drove both the low pressure compressor and the power shaft was investigated (Figure 4). This configuration was abandoned for similar reasons.

Other arrangements were also evaluated including split systems where two combustors and two recuperators could be used to optimize the temperatures at each turbine section. One of these variants is depicted in Figure 5 for illustrative purposes. This system did not provide any significant improvements over the more traditional arrangements due primarily to the high temperatures imposed on the power turbine. The cooling air flow required for the power turbine exceeded that needed for the baseline configuration turbines. Thus the two primary configurations that were initially considered and used as baselines were the only ones judged likely to succeed in meeting all of the ATS50 program goals.

2.3 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. Additional information concerning materials of construction and material selection logic is presented in Section 4.

2.3.1 Low Pressure Compressor

The compressor segment in all configurations is divided into two sections, a low pressure section and a high pressure section. 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.

Current industrial gas turbine materials of construction for the two-spool LP compressor will most likely be ferrous alloys for the blades, disks, vanes and casings. There is little corrosion potential at the inlet to the low -pressure compressor; however, at the inlet to the high pressure compressor, the air is likely to be saturated with water. The variable inlet guide vanes and the first blade rows of the high pressure compressor will be coated with materials that resist both corrosion and erosion.

2.3.2 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.

There are two principal heat exchange configurations for an intercooler. These are generally referred to as direct heat exchange and indirect heat exchange. There is a considerable difference between the two types both in terms of performance and in the size of the equipment. The direct-transfer type is a simple heat exchanger in which the two fluids are separated by the heat transfer surface. Generally this type of heat exchanger when used as an intercooler is an air-to-air unit. The indirect-transfer system is simply two direct-transfer units coupled together by a pumped heat transfer medium. Intercoolers on gas turbines are usually of the indirect-transfer type and use liquid coolants such as water/glycol mixtures as the heat transfer medium. These coolants remove the energy from the compressed air in the first heat exchanger and reject the heat absorbed to the ambient atmosphere or to some other heat sink (water or air) through the second heat exchanger. The energy rejected to the ambient can be recovered in a bottoming cycle, if desired. Solar has selected the indirect-type heat exchanger because of its ability to reduce the size of the two individual heat exchange devices and the possible use of a large variety of heat sinks. This ability allows site-specific application of the ICR system.

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.

2.3.3 High Pressure Compressor

Following the intercooler is the high pressure (HP) compressor. This is likely to be constructed as an axial system (see discussion below for comparison to a radial design system). For an overall engine pressure ratio of between 12:1 and 16:1 the axial HP compressor 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. The decision on whether to use a radial high pressure compressor will be made during Task 6 System Definition and Analysis.

The materials used in the construction of the high pressure compressor will be similar to those used in the low pressure compressor, i.e., standard IGT materials. In both the one- and two-spool versions, the first stages of the HP compressor may be fabricated from nickel-based alloys to minimize erosion and corrosion from water and condensates that can be carried to the compressor from the intercooler.

2.3.4 Recuperator

The air leaving the high pressure compressor is ducted to a recuperator where it is heated before it enters the combustor. The recuperator is a heat exchanger that is used to transfer waste thermal energy from the engine exhaust gases to the high pressure inlet air. There are many types of heat exchangers that can be employed as gas turbine recuperators, including shell-and-tube, brazed plate-fin and primary surface recuperator (PSR). From the various types of heat exchangers, Solar has selected a compact surface, all welded, primary surface type of recuperator that offers significant advantages both in small size and high effectiveness when compared to the other systems. The PSR offers the combined advantages of high effectiveness, low weight and volume, low maintenance and high reliability. 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 predicted effectiveness of 90 percent. This calculated 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 the increased the size and cost of the recuperator.

The pressure losses associated with the recuperator are modest, with 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.

The materials of construction for the recuperator are covered in Section 4.

2.3.5 Low Emissions Combustor

As mentioned in Section 1.0, 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, much like most low emission systems, relies on premixing of the air (Figure 6) and fuel before it enters the combustor.

Although the combustor inlet conditions affect NOx production in complex ways, it is the probability of autoignition and flashback during premixing that is most influenced by the operating conditions. Therefore, premixing considerations tend to favor selecting lower pressures and temperatures at the combustor inlet. Higher combustion system inlet pressures and temperatures increase developmental risk, because complete fuel/air mixing must be accomplished more quickly to avoid autoignition and flashback.

The work performed to date by Solar on subscale models (at pressures up to 14 atmospheres) has demonstrated that catalytic combustion can provide exceptionally low NOx levels. The system is expected to operate at the higher pressures of the ATS without any significant problems. These tests have indicated that the oxidation catalysts have to be tailored to the particular fuel and specific operating conditions. Once the optimum catalyst has been identified for the ATS environment (methane), Solar is confident that emission levels of NOx lower than the ATS50 program goal of eight ppmv can be achieved.

Figure 6. Catalytic Combustor Design for ATS

A typical catalytic oxidation reactor is fabricated using a ceramic or metallic honeycomb monolith having a large number of parallel, square-sectioned passages. These passages or channels are coated with a platinum-based material that catalyzes the reaction of the fuel and air. The catalysis process essentially involves the acceleration of the intrinsic reaction rate between the fuel and oxygen. This allows operation at fuel-air ratios that are below the lean extinction limit for conventional combustion systems. One major benefit of the catalytic system is that it uses no water as part of the process.

As a means of risk reduction, an ultra-lean premixed combustion system will be developed for ATS in parallel with the catalytic system. The ultra-lean premixed approach will extend the technology used in low-emissions gas turbine combustors just now entering the marketplace. Several of these systems, including Solar's SoLoNOx combustion systems, have shown NOx emissions capabilities below 10 ppmv at discrete operating points. Optimization of the fuel/air premixing process, reduction of CO formation near the combustor liner wall through the use of ceramic combustors, and better combustion control through combustor variable geometry, will all improve the low emissions capabilities of the lean premixed approach. Technical challenges include premixing without autoignition at high combustor inlet temperatures, lean combustion without unacceptable combustor pressure fluctuations, and achieving sufficiently low pattern factors with reduced amounts of dilution air. All of these areas will be addressed in the planned Phase III development work to ensure the availability of a low-emissions combustion system for the ATS.

Another approach, called autothermal reformation, involves the use of chemical recuperation to reform a steam/fuel mixture. In this way, about 16 percent of the energy in the engine exhaust, is converted into fuel (chemical) energy. Although Solar does not anticipate employing chemical recuperation in ATS50, it will be considered along with other future efficiency enhancements as they become technically viable and acceptable in the marketplace.

2.3.6 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.

2.3.6.1 Gas Producer Turbine Section

The gas producer turbine section consist of one or more turbine stages which drive the compression section of the engine. The gas producer is a single-stage, high-pressure (HP) turbine and single-stage, low-pressure (LP) turbine in the case of the two-spool configuration, and a single-stage HP turbine for the one-spool configuration. A turbine stage is made up of stationary and rotating hardware. The stationary hardware includes nozzle guide vanes and gas-path walls. The blades, disk, and related seals comprise the rotating hardware of a turbine stage.

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 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 superalloy outer rim HIP bonded to a more conventional material inner disk, allows for operating at rim temperatures of approximately 1500°F, while maintaining life requirements. 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.

2.3.6.2 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 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.

2.4 CONFIGURATION AND CYCLE SELECTION

This section of this document defines the process of selecting the engine configuration and cycle for the ATS program. In this section, the engine configuration is the number and arrangement (mechanical linkage and flow path) of components. The cycle is the combination of design parameters such as overall compressor pressure ratio (PR), turbine rotor inlet temperature (TRIT),

etc., for a given configuration. This configuration and cycle selection process is designed to identify the configuration and cycle which most closely meets the stated program goals for the ATS 50 (Table 2).

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 can 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 7 and 8 show plots of efficiency vs. PR at lines of constant TRIT for both the one-spool and two-spool configurations of the engines.

Figure 7. 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.

Figure 8. 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.

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. The following tables show the results of these sensitivities.

Table 4. Sensitivity of Overall Efficiency to Changes in Component Efficiency, Pressure Losses, Etc.

Sensitivity to Changes in Component Efficiencies Pressure Losses, Etc.		Changes in Overall Thermal Efficiency					
		Two-Spool Cycles (PR/TRIT) (%)			One-Spool Cycles (PR/TRIT) (%)		
		20:1/2500	16:1/2500	12:1/2450	20:1/2550	16:1/2500	12:1/2500
Cycle Parameter	Change						
LPC Efficiency	+0.5	+0.12	+0.10	+0.90	+0.11	0.11	0.09
	-0.5	-0.12	-0.10	-0.09	-0.12	-0.11	-0.09
HPC Efficiency	+0.5	+0.14	+0.13	+0.12	+0.14	+0.13	+0.12
	-0.5	-0.14	-0.13	-0.12	-0.14	-0.14	-0.12
Intercooler Effectiveness	+1.0	+0.08	+0.08	+0.05	+0.08	+0.07	+0.06
	-1.0	-0.08	-0.08	-0.05	-0.08	-0.07	-0.05
Recuperator Effectiveness	+1.0	+0.17	+0.20	+0.24	+0.18	+0.22	+0.27
	-1.0	-0.17	-0.20	-0.24	-0.18	-0.22	-0.27
Combustor Efficiency	+0.5	+0.24	+0.24	+0.27	+0.27	+0.24	+0.24
	-0.5	-0.24	-0.24	-0.24	-0.24	-0.24	-0.24
HPT Efficiency	+0.5	+0.08	+0.05	+0.05	+0.11	+0.11	+0.10
	-0.5	-0.08	-0.05	-0.05	-0.11	-0.11	-0.10
LPT Efficiency	+0.5	+0.04	+0.04	+0.03	N/A	N/A	N/A
	-0.5	-0.05	-0.04	-0.03	N/A	N/A	N/A
Power Turbine Efficiency	+0.5	+0.17	+0.17	+0.17	+0.17	+0.17	+0.17
	-0.5	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17
Typical Pressure Loss	+0.5	+0.07	+0.08	+0.09	+0.07	+0.08	+0.09
	-0.5	-0.07	-0.08	-0.09	-0.07	-0.08	-0.09
Reductions in Total Cooling Flow	-10.0	+0.54	+0.59	+0.65	+0.60	+0.54	+0.61
	-20.0	+1.07	+1.18	+1.30	+1.20	+1.08	+1.22

Based upon these optimization and sensitivity studies, the most promising cycles were selected for further evaluation toward the goals of the program. The selected cycles for the two-spool gas generator configurations were 14:1, 16: 1, and 18:1 Rc, at the optimum TRIT (2450°F for all three), and compressor work split. The 20:1 cycle was eliminated immediately, as this pressure was higher than allowable for both the recuperator and the combustion systems which will be used in the ATS engine. The selected cycles for the one-spool gas generator configuration were 14:1 and 16:1 Rc, at optimum TRIT (2500°F in both cases), and compressor work split.

In evaluating the cycles against the goals of the program, four areas of interest were identified. The first three areas involved direct comparison of the engines with respect to the efficiency, cost, and reliability, availability, maintainability and durability (RAMD) goals of the program. These goals were

divided into subcategories, each of which was assigned weighting factors. The sum total of the weighting factors for each goal was 35, so that each goal carried an equal weight in the decision.

The final area of assessment involved determining the difficulty in achieving the emissions and efficiency goals of the program. For the emissions goals, this meant estimating the risks of the combustion technology at the pressures involved. Problems considered included preignition, combustor life, pattern factors, etc. For the efficiency goal, the assessment was made based on the technology improvements required get to the 50% overall efficiency goal. This involved determining combinations of component efficiency improvements, reductions in cooling flow, and reductions in pressure loss which were required to get the overall efficiency of each of the cycles to 50%.

Each of the criteria was assigned a rating from zero to ten, ten being the highest possible. To determine the final ranking, each rating was multiplied by the weighting factor, and the results were summed to get the final score for each of the candidate cycles. The results of the assessments are shown in Table 5.

2.5 ACHIEVING 50 PERCENT OVERALL THERMAL EFFICIENCY

As can be seen from the plots above, neither of the cycles selected achieve the 50 percent efficiency goal. However, in doing the preliminary design work for the studies, some of the values for component efficiency, pressure losses, cooling flows, etc., included technology improvements expected to be achievable by the year 2000, and some did not. This had no effect on the outcome of the studies being done, as the purpose of the studies was to determine the cycle with the best overall efficiency, not the level of that efficiency.

Part of the refinement process being undertaken following the cycle selection is to identify the year 2000 technology improvements for all components, cooling, pressure losses, etc. A determination can then be made whether those available technology improvements alone are sufficient to make the 50 percent goal, or if additional effort will be required.

Table 5. Cycle Selection Decision Matrix

Cycle Selection Decision Matrix		Score by Configuration				
		Two-Spool Cycles (PR/TRJT)			One-Spool Cycles (PR/TRJT)	
		18:1/2450	16:1/2450	14:1/2450	16:1/2500	14:1/2500
Engine Goals	Relative Weight					
Overall Efficiency Goal						
Thermal Efficiency at Design Point	14	8	7	5	9	7
Part Load Thermal Efficiency	5	8	8	8	5	5
Potential for Efficiency Improvement	6	8	7	6	7	6
Thermal Efficiency vs. Ambient Temperature	5	7	7	7	8	8
Insensitivity to Component Changes	5	5	5	5	4	4
Overall Efficiency Subtotal		260	240	206	253	219
Cost of Power Goal						
Mechanical Complexity	8	4	4	5	7	7
Control Complexity	7	6	6	7	8	9
Overall Parts Count	4	4	5	5	6	6
Number of Hot Section Parts	6	4	4	4	5	5
Potential for Hot Section Access	5	4	4	4	5	5
Overhaul Cost	5	5	5	5	6	6
Cost of Power Subtotal		159	163	178	221	228
Reliability, Availability, Maintainability						
Control System	7	7	7	7	8	8
Compressor Aerodynamics	4	9	9	9	7	7
Recuperator Performance/Life	6	4	6	8	5	6
Combustion System	5	8	9	9	8	9
Turbine Aerodynamics	5	8	7	6	7	6
Mechanical Design	4	6	7	7	8	8
Manufacturing	4	6	7	7	8	8
RAM Subtotal		237	257	264	253	259
Difficulty in Achieving Program Goals						
Efficiency	35	5	4	2	7	5
Emissions	35	4	5	6	5	6
Difficulty in Achieving Goals Subtotal		315	315	280	420	385
Grand Totals		971	975	928	1147	1091

3. CRITICAL COMPONENTS AND TECHNOLOGIES

There are four components that are considered to be technologically significant to the ATS;

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

Each of the first three components utilizes heat transfer technologies of one form or another, and each is critical to meeting the 50 percent thermal efficiency goal. The catalytic combustion technology selected has neither been demonstrated in a full-size system nor at the full system pressure. These are important issues and will be resolved through experimental testing.

3.1 COOLED TURBINE BLADES

Extensive consideration was given to the method of cooling the ATS50 gas producer turbine and power turbine first-stage blades. Due to the high TRIT, the bulk of the overall engine cooling air flow was required to maintain the blades at acceptable temperature levels. It was also essential that the amount of cooling air utilized for the cooled blades was consistent with meeting the thermal performance goals of the ATS50.

Two different cooling arrangements were considered. The first of these was to use ceramic blades and the second was to use metallic single crystal alloy blades. The ceramic configuration resulted in the lowest cooling flow budget, however, there is a significantly 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 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.

Based on the results of the forthcoming heat transfer tests at Solar the blade cooling configurations will be optimized in an effort to reduce cooling flows and increase thermal efficiency. The current blade cooling designs have sufficient flexibility built into them, that major redesigns are not likely.

3.2 RECUPERATOR

The recuperator selected for the ATS50 is the all primary surface heat exchange system that Solar has produced for several years. The ATS50 primary surface recuperator (PSR) will use appropriate materials required to meet system specifications. As temperatures and pressures increase, material properties must be increased. This may mean the use of some higher quality alloys, such as Inconel 625, or combinations of materials.

3.3 INTERCOOLER

The use of an intercooler positioned between two conventional compressors provides near isothermal operation and substantially reduces the energy requirements for compression. 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 of 0.075 percent. The overall effect of a 70-to-85 percent intercooler effectiveness change would increase the cycle efficiency by only 1.125 percent.

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. A cooling tower using evaporative cooling 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 water would be needed for an ATS cooling tower. Data will be collected during the Task 5 Market Study to determine to how many customers this approach would be acceptable.

3.4 CATALYTIC COMBUSTION SYSTEM

The catalytic combustion system is the preferred method of meeting the ATS50 NO_x goals. Because water injection is not required, lower pattern factors can be achieved, and the likelihood of stable combustion over the entire system operating range is high. Risk with catalytic combustion is associated mostly with the integration of this technology into the ATS, and the life of the catalytic reactor at ATS conditions. Despite these concerns, the catalytic combustion system offers the lowest NO_x levels (as low as two parts-per-million by volume under laboratory conditions) of any alternative. The planned experimental investigations into the behavior of the catalytic system at pressures typical of ATS50 operation (16:1) will provide design guidelines to address these technology and integration issues. In parallel, work will be performed with the ultra-lean premixed approach to ensure that there is an alternative path to commercialization.

3.5 OTHER SYSTEMS

Although a reheat combustor is not considered to be a critical component for the ATS50 it will be crucial for the future generation ATS products as they become acceptable in the marketplace. Similarly the potential use of an autothermal reformer to chemically recuperate the ATS and boost efficiency levels will also be critical in attaining efficiencies greater than 50 percent. The component issues with these two add-on systems are being addressed experimentally in Task 8. The reheat combustor requires the development of new high temperature materials of construction before it becomes practical for operation in an ATS environment. These new materials will be used to construct uncooled combustor walls that will have to operate at temperatures between 2800-and-3000°F. If these material developments are successful then the use of a reheat combustor as part of the ATS50 will be reevaluated at the end of Phase II.

One of the critical material requirements of the autothermal reformer, is the development of a sulfur-tolerant catalyst. Sulfur is known to poison all the catalysts presently in industrial use for the commercial steam/methane reformation processes. Sulfur-tolerant catalysts will have to be developed because there is no control over sulfur content in natural gas. Removal of the sulfur compounds raises a solid waste disposal issue and thus is preferably avoided. Sulfur tolerance will provide the life needed by the autothermal reformer to be considered suitable for integration with the ATS50. The ongoing experimental evaluation of reformer catalysts (Task 8 Design and Test of Critical Components) is addressing the sulfur tolerance problem and is demonstrating excellent results. Combustor integration and operation problems are also foreseen due to the high-hydrogen-content secondary fuel that is produced. Safety concerns with hydrogen containment and flashback need to be solved. Once the material issues have been resolved then the problems of operation and integration will be addressed.

4.0 MATERIAL SELECTIONS

Availability of Advanced Materials and Processes, and the corresponding design methodologies to effectively utilize these materials, are critical to meeting the goals of ATS. Many of the required materials development and characterization programs are currently underway and significant progress has been made (e.g., CSGT, ARPA TRP programs, and D.O.E. CRADAS). Additional critical path technology development programs have been identified, some of which have been described in the requirements for the ATS baseline Task 8 and the Add-on Task 8 - Design and Test of Critical Components, and others of which may be internally funded. The integration of these critical technologies and materials developments into the overall engine system, will assure that the goals of the ATS program can be met.

The primary material selection challenges of the ATS engine fall in the areas of the GP turbine components, the catalytic combustor, and the recuperator. The GP turbine components include nozzles, blades, disks, seals, and stationary structures such as casings, ducting and interstage "diaphragm" structures. A preliminary review of candidate materials for these various components has been completed, and is attached for reference in Appendix B. This "first-cut" look at candidate materials identifies potential temperature, stress and oxidation limits for a life of 8,000 hours. This relatively short component life assumption was chosen in order to identify the maximum potential temperature of the various materials for comparative purposes. Additional analysis of the actual design life will be performed in Phase II Task 6- System Definition and Analysis and Phase III of the ATS program.

Based on review of the current engine cycle requirements (one- and two-spool configurations), some preliminary material selections have been made from the candidate materials. Table 6 summarizes this effort for several of the critical ATS components. The table lists both the preferred, or primary, materials selection for the various components, and also first and second alternatives. Having alternative materials developed in parallel with the primary choice is considered important for reducing the risk associated with the aggressive program goals. Also indicated (by an asterisk) are the materials which may be acceptable immediately for reaching the ATS50 efficiency goals.

4.1 TURBINE BLADES

The preferred material for the GP Turbine blades for the 2450°F TRIT engine would be monolithic ceramics. The principal advantage they possess over their metallic counterparts is their ability to retain their structural integrity with reduced, or potentially eliminated, cooling flows. Ceramics are also less prone to environmental degradation when compared to metals under these extreme conditions. Secondary benefits relative to metal blades include their low density (and thus lower disk-post stresses), and they contain no alloying elements considered "strategic" as most superalloys do.

Among the candidate ceramics, silicon nitride would currently be the material of choice for the blade because of their superior strength and thermal shock resistance as compared to the carbides and oxides. Silicon nitride is being strongly considered for the blade under the CSGT program. For the ATS program, advancements in carbide-based ceramics will be monitored closely because of their potential use at even higher temperatures than nitrides.

**Table 6. Summary of Preliminary Material Selections for Critical
ATS Hot Section Components**

Engine Component	Primary Selection	First Alternative	Second Alternative
GP Turbine Section a. Blades b. Nozzles c. Disks d. Seals	Ceramics ¹ Ceramics ² Dual-property disk [*] FGM ceramics	Cooled CMSX-4 [*] Cooled CMSX-4 [*] Coarse-grain U-720 Zr-based coatings [*]	Cooled CMSX-4 + TBC Cooled CMSX-4 + TBC Waspaloy MCrAlY coatings
Recuperator	Dual material Inconel 625/347 SS	Inconel 624 [*]	Haynes Alloy 230
Combustor	Carbide or BZP ceramic [*]	Metallic W/ FGM	Cooler superalloy ³
Ducts	Monolithic ceramic (SiC)	Oxide/oxide CFCC	Cooled superalloy ³
<p>[*] Denotes material choice which may be acceptable for ATS 50 requirements.</p> <p>Notes:</p> <p>¹Candidates are nitride and carbide ceramics; cooled or uncooled depending on turbine stage.</p> <p>²Candidates are toughened nitride, carbide and CFCC ceramics; cooled or uncooled depending on turbine stage.</p> <p>³Candidates are Hastelloy X, Haynes Alloy 230 and oxide dispersion strengthened superalloys.</p>			

If metal blades are used, state of the art single crystal CMSX-4 will be the material of choice. Advanced cooling systems will be incorporated for the early stages of the turbine, however, solid single crystals may be an option in cooler later stages. Electron Beam Plasma Deposition Vapor (EB PVD) thermal barrier coatings are being evaluated as an option in the event that advanced cooling alone does not provide sufficient temperature reduction. Functionally Graded Materials (FGMs) and "tuned" emissivity coatings are horizon material options which will be considered for the application.

The ability to drill laser cooling holes is being investigated under the CSGT program. If this process is proven out, the cooled silicon nitride blade will provide a very attractive option. Material development is proceeding at a rapid rate and better oxidation resistant varieties of silicon nitride are already being produced by Solar's CSGT subcontractors Kyocera and Ceramic Components (Division of Allied Signal).

4.2 NOZZLES

Because the peak temperature of the nozzles is likely to be higher than the blade, ceramics could play an even more important role in these components due to their good thermal resistance. Cooled ceramic nozzles are currently being considered in the CSGT nozzle design effort and the assimilated knowledge on this subject will feed directly into the ATS program. Depending upon material advancements and exact engine conditions, using uncooled ceramic nozzles is the goal for ATS50.

The silicon nitrides and silicon carbides will both be considered for nozzles, with each material having their advantages and disadvantages. While silicon carbides like Hexoloy SA are more stable in retaining their strengths as a function of time, their maximum strength levels are usually much lower than the leading silicon nitrides. The improved fabricability of silicon nitride nozzles relative

to silicon carbides, and the greater number of market ready materials make silicon nitride the current material of choice. However, future developments of the silicon carbides will be monitored closely since this material offers a significant temperature/strength advantage.

4.3 TURBINE DISKS

In order to obtain maximum benefit from the use of uncooled nozzles and blades discussed above, it is essential that turbine disk materials be developed which can also operate with reduced cooling requirements. Reducing the cooling flow to the turbine disk not only improves the overall engine efficiency, but has the secondary advantage of improving the radial temperature profile to the nozzles. Reducing the radial temperature gradient across the nozzle dramatically lowers the thermal stress imposed on the nozzle material, resulting in durability benefits. Excessive thermal stress could make the application of ceramic nozzles impractical from a design standpoint. Therefore, development of turbine disk materials which can operate at significantly higher rim temperatures is considered an enabling technology for effective utilization of ceramic nozzles.

The method proposed to attain the goal of higher disk rim operating temperatures will follow two technical paths. One path is considered a relatively low risk, near term solution with moderate-to-high payoff, involving an isothermally forged high-strength cast-wrought disk alloy, Udmet 720. The other path is a somewhat higher risk approach, but with a very high payoff potential. This involves a dual-property solution wherein two different materials are HIP-bonded together.

Udmet 720 is expected to provide a disk rim capable of operating at temperature greater than 1400°F. This temperature estimate is based on a disk-post stress prediction by CSGT Design Engineering of 20 KSI using ceramic blades, and a stress rupture life of 100,000 hours. The development of Udmet 720 for this type of application has been initiated under a Solar internally funded program. Operation at rim temperatures higher than that allowed by high strength wrought alloys, such as Udmet 720, necessitates the use of a material with creep properties equivalent to the cast superalloys typically used for turbine blades. This can be accomplished by HIP bonding a cast ring produced in a blade alloy to a fine-grain bore material optimized for hub properties. In the proposed ATS Add-on Task 8 program, the technical approach and feasibility of the dual-property disk has been fully reviewed. The goal for this combination of materials is to enable a continuous rim operating temperature greater than 1500°F, again assuming a 20 KSI disk post stress (i.e., ceramic blade) and 100,000 hour service life.

4.4 RECUPERATOR

Initial cycle analyses of the one- and two-spool configurations indicate that Solar's standard material of construction, Type 347 stainless steel, may have insufficient creep strength for the ATS50 application. However, these are continuing and some of the combinations of pressure ratio and TRIT look promising. For example, a cycle with a recuperator metal temperature of 1050-to-1100°F, and a 16:1 pressure ratio can use a Type 347 SS recuperator. However, as pressure and temperature increase, Inconel 625 may be required to provide a comfortable strength margin for ATS50. Inconel 625 is a well characterized nickel-base superalloy with high strength and excellent fabricability, and is used extensively in industrial gas turbines.

Solar has proposed a cost-reducing measure in the Add-on Task 8 effort involving a dual-material approach wherein the relatively expensive nickel alloy is confined only to the highest temperature region of the recuperator. As the heat exchange process lowers the temperature sufficiently, Type 347 stainless steel would be utilized. This approach may provide the required material properties at a significantly reduced overall system cost.

5. CONCLUSIONS AND RECOMMENDATIONS

After the year 2000, the marketplace requirements will change considerably from those existing today. Reliability, availability, maintainability and durability (RAMD) will probably remain at the top of the customer requirements list; however, first-cost (typically in second place) today will decrease in importance and will be overtaken by the threshold issue of emissions. Life-cycle cost (cost of power) will become increasingly more important as efficiency and conservation become legislated requirements. These estimates of future customer needs coincide well with the goals of the ATS program, which were given earlier in Table 1.

The best approach preliminarily identified by Solar's System Selection Team is a one-spool engine with a pressure ratio of 16:1 and a turbine rotor inlet temperature of 2500°F. The alternative approach was the two-spool system again with a pressure ratio of 16:1 and a turbine rotor inlet temperature of 2450°F. An important differentiator between the one- and two-spool systems is the additional cooled turbine stage required by the two-spool approach. This additional stage increases the amount of cooling air bled from the high pressure compressor over that needed for the one-spool configuration. The increased bleed flow reduces the base efficiency, thus making it more difficult to achieve the 50 percent thermal efficiency goal. The one-spool has the additional advantage of simplicity; while the primary advantage of the two-spool approach is that it has much better part-load efficiency characteristics.

The operational utilization of ATS50 is likely to be the ultimate, deciding factor in the selection process. If the operational requirements favor base-loading, then the one-spool will be the better engine system. If considerable time is spent at part-power conditions, such as with load-following applications, then the two-spool system may be favored. However, both the one-spool and two-spool approaches will be retained for design in Task 6 System Definition and Analysis until more refined market requirement data are available from the Task 5 Market Study. Thus, the two engine systems that will be designed in Task 6 will both have about the same pressure ratio (16:1) and the same turbine rotor inlet temperature (2500°F); but one will have a one-spool configuration while the other will have two spools. Both approaches will utilize a free power turbine. Both approaches will employ similar catalytic combustion systems and a similar recuperator and intercooler.

The critical components as identified above are the intercooled compressor, recuperator, GP turbine blades, and the combustor. The risk associated with the application of an intercooled compressor is considered medium. The only application hurdle is the possible presence of water droplets in the HPC inlet stream. Two alternatives, demisters and a compressor design change, have been identified.

Achieving the required recuperator performance is considered a low risk. The primary problem facing the recuperator will be one of attaining acceptable life at an acceptable cost. Cycle conditions in combination with carefully selected materials for the current ATS50 recuperator indicates that acceptable creep life can be achieved. Additional work is being performed in Task 8 Analytical and Materials Test to confirm these selections.

Turbine blade cooling performance needs are considered to be a challenge for advanced convective cooling schemes. Recently developed long-life thermal barrier coatings can be applied to the blades to meet this challenge. There is a chance of not meeting performance with the proposed turbine blade cooling system with the development blades. However, with further development, these convective cooling designs should prove to be successful. Uncooled or low-flow cooled ceramic

blades will be adopted for ATS when they are developed to the point that incorporation will not pose additional risk.

Catalytic combustion is considered to be a high risk, high pay-off element of the ATS (see Table 7). The present sub-scale systems have yet to be demonstrated at the ATS conditions. However, the ongoing ATS Phase II and planned Phase III experimental evaluations of catalytic combustion are structured to address the technology and integration issues which could hinder development within the program schedule. Ultra-lean premixed combustion will be developed in parallel with catalytic combustion to reduce overall program risk and increase the opportunity for technology spin-offs to other commercial gas turbine systems. The Phase III program plan includes a decision point at which the suitability of catalytic combustion for ATS is reaffirmed.

Table 7. ATS Component Risk Factors

PROGRAM GOAL	ELEMENTS	LEVEL OF DIFFICULTY AND RISK MANAGEMENT	
50% Thermal Efficiency	Firing Temp.	High (Hot section life).	Realistic material choices. Borrow from CSGT. Incremental TRIT testing. Test in existing products.
	Cooling	High (Hot section life).	Incremental improvement to existing technologies. Materials development. Test in existing products.
	Component Aerothermal Efficiency	Medium (Attainment)	Improved design analysis.
	Pressure Ratio	Low (Recuperator?)	
8 ppmv NOx	Combustion Technology	High (Attainment). (Durability)	Retain options (Catalytic, ATR, Lean Premixed, Rich-Lean) Improved design analysis.
15 ppmv CO	Combustion Technology	Medium (Comb. life).	Retain options (Wall materials, advanced cooling, film cooling)
15 ppmv UHC	Combustion Technology	Medium (Comb. life).	Improved design analysis
	Lubrication Systems	Medium (Durability).	Advanced lubricants/Improved seal technologies
10% Reduced Cost of Power	O & M Costs	Medium (Efficiency, Durability)	Update cycle analysis Tradeoff analysis
	First Cost	Medium (Efficiency, Durability)	Update cycle analysis. Tradeoff analysis
	RAMD	Low (Attainment)	Design data acquisition into package.
	All governed by: - mechanical design - production processes - materials - customer services		

APPENDIX A

A.1 ATS Conventional One Spool

 Ambient: Engine Ambient
 Amb Temp 59.000 Amb Press 14.696
 Rel Humid 60.0% Spec Humid .00634
 Day: User Input Altitude zero
 Temp Adder zero Press Adder zero

 Overall Performance
 Total HP Output 16092.0
 Tot Fuel 4021.7 Heat Rate 82.89M
 Fuel SFC .24992 H.R. SFC 5.151k
 Over Eff .49398 Spec SHP 287.37

Compressor/Turbine Name	Refrd AirFlow	Press Ratio	Adiab Eff	Polyt Eff	Power	Physcl Speed	Refrd Speed	Refrnc Speed	Pot Ref Speed
LPC	55.997	3.2400	.87303	.89190	4522.7	n/a	n/a	n/a	n/a
HPC	18.600	5.0910	.89846	.91840	6953.0	n/a	n/a	n/a	n/a
HPT	8.4657	2.6599	.86200		11592	n/a	n/a	n/a	n/a
Power Turbine	21.329	5.2721	.90300		16255.	n/a	n/a	n/a	n/a

Station Name	Total Press	Total Temp	Physcl Flow	Rfrd Flow	Total Enthlp	Fuel Air Ratio	Entrpy BTU/lR	Heat Capcty BTU/lR	Bleed In	Bleed Out
	psia	deg F	lbm/s	lbm/s	BTU/lb				lbm/s	lbm/s
S0	14.696	59.000	n/a	n/a	-4.344	zero	1.5964	.24129		
S1_0	14.696	59.000	55.997	55.997	-4.344	zero	1.5964	.24129		
S1_3	47.615	294.42	55.997	20.839	52.741	zero	1.6871	.24418		
S1_4	47.377	294.42	55.997	20.944	52.741	zero	1.6871	.24418		
S1_6	45.956	94.313	55.997	18.507	4.1805	zero	1.6123	.24153		
S1_7	45.726	94.313	55.997	18.600	4.1805	zero	1.6123	.24153		
S2_0	232.79	453.85	50.266	4.2114	91.942	zero	1.7343	.24778		5.7307
S2_1	230.46	453.85	50.266	4.2539	91.942	zero	1.7343	.24778		
S2_4	225.85	1119.7	50.266	5.7074	263.71	zero	1.8750	.26836		
S2_5	223.59	1119.7	50.266	5.7651	263.71	zero	1.8750	.26836		
S3_0	221.36	2532.4	51.383	8.1934	701.59	.02222	2.1005	.31494		
S3_1	216.93	2500.0	52.313	8.4657	690.75	.02182	2.0963	.31413	.92955	
S5_0	81.557	1994.9	52.313	20.506	534.14	.02182	2.0383	.30554		
S5_05	81.557	1922.5	55.232	21.329	510.77	.02064	2.0271	.30315	2.9196	
S5_1	81.557	1922.5	55.232	21.329	510.77	.02064	2.0271	.30315		
S6_0	15.469	1193.6	57.114	96.872	295.82	.01995	1.9187	.28360	1.8816	
S7_0	14.696	642.25	57.114	83.248	144.64	.01995	1.8078	.26431		

Compressor: LPC
 Prss Ratio 3.240 Ref Airflw 56.00
 Adiab Eff .8730 Polyt Eff .8919
 Del h/thet 57.09 Del T/T .4539
 Phys Speed n/a Ref Speed n/a
 ‡ Ref Spd n/a (Refnce N n/a)
 Power Required 4523.
 Clearance n/a Reynold's n/a
 Beta zero
 GV Angle zero GV Dlt Sch zero
 CS SM (1) n/a CA SM (1) n/a

Intercooler: LPC Cooler
 Heat Trans 2719. Effectvns .8500
 Temperatures Entrance Exit
 Engine Flow 294.419 94.3129
 Coolant Flow 59.0000 107.560
 Heat Trans Type: Effectiveness Inp
 Press Loss: User Input
 Pressure Loss .03000

Duct Name Press
 IC_Inlet .0050
 IC_Exit .0050
 Recup_Inlet .0100
 Recup_Exit .0100
 Burn-HPT .0200
 HPT_Blade_Bleed zero
 HPT-PWT zero

Compressor: HPC
 Prss Ratio 5.091 Ref Airflw 18.60
 Adiab Eff .8985 Polyt Eff .9184
 Del h/thet 82.17 Del T/T .6490
 Phys Speed n/a Ref Speed n/a
 ‡ Ref Spd n/a (Refnce N n/a)
 Power Required 6953.
 Clearance n/a Reynold's n/a
 Beta zero
 GV Angle zero GV Dlt Sch zero
 CS SM (1) n/a CA SM (1) n/a

Recuperator: Recup
 Heat Trans 8634. Effectvns .9000
 Temperatures Entrance Exit
 Core Flow 453.850 1119.65
 Exhaust Flow 1193.64 642.250
 Heat Trans Type: Effectiveness Inp
 Press Loss Data Core Exhaust
 Press Loss Type: Input Input
 Pressure Loss .020000 .050000

Combustor: Burner
 Exit Temp 2532.4
 Fuel Flow 4022. Fuel/Air .0222
 Efficiency .9900 Press Loss .0100
 Press Loss: User Input
 Fuel Type: User Input
 Fuel LHV 20610 Fuel HCR .3200

Turbine: HPT
 Prss Ratio 2.660 Ref Airflw 8.466
 Efficiency .8620
 Rfrd Torq n/a Dlt h/thet 27.45
 Phys Speed n/a Ref Speed n/a
 ‡ Ref Spd n/a (Refnce N n/a)
 Power Dlvr 11592 Work Coeff zero
 Clearance n/a Reynold's n/a
 Limit Loading n/a

Turbine: Power Turbine
 Prss Ratio 5.272 Ref Airflw 21.33
 Efficiency .9030
 Rfrd Torq n/a Dlt h/thet 45.29
 Phys Speed n/a Ref Speed n/a
 ‡ Ref Spd n/a (Refnce N n/a)
 Power Dlvr 16255 Work Coeff zero
 Clearance n/a Reynold's n/a
 Limit Loading n/a

Efficiency Type: Adiabatic Efficiency
 Prss Ratio Calc Uses: Exit Pstatc
 (Balancing Turbine)

Efficiency Type: Adiabatic Efficiency
 Prss Ratio Calc Uses: Exit Pstatc
 (Balancing Turbine)

A.2 ATS Advanced One Spool

 Ambient: Engine Ambient
 Amb Temp 59.000 Amb Press 14.696
 Rel Humid 60.0% Spec Humid .00634
 Day: User Input Altitude zero
 Temp Adder zero Press Adder zero

 Overall Performance
 Total HP Output 16092.0
 Tot Fuel 3973.6 Heat Rate 81.90M
 Fuel SFC .24693 H.R. SFC 5.089k
 Over Eff .49996 Spec SHP 293.12

Compressor/Turbine Name	Refrd AirFlow	Press Ratio	Adiab Eff	Polyt Eff	Power	Physcl Speed	Refrd Speed	Refrnc Speed	Pct Ref Speed
LPC	54.900	3.2400	.87303	.91840	4434.0	n/a	n/a	n/a	n/a
HPC	18.235	5.0910	.89846	.91840	6816.8	n/a	n/a	n/a	n/a
HPT	8.3319	2.6319	.86700		11364.	n/a	n/a	n/a	n/a
Power_Turbine	20.745	5.3282	.91300		16255.	n/a	n/a	n/a	n/a

Station Name	Total Press	Total Temp	Physcl Flow	Rfrd Flow	Total Enthalp	Fuel Air Ratio	Entrpy BTU/lR	Heat Capcty BTU/lR	Bleed In lbm/s	Bleed Out lbm/s
S0	14.696	59.000	n/a	n/a	-4.344	zero	1.5964	.24129		
S1_0	14.696	59.000	54.900	54.900	-4.344	zero	1.5964	.24129		
S1_3	47.615	294.42	54.900	20.431	52.741	zero	1.6871	.24418		
S1_4	47.377	294.42	54.900	20.534	52.741	zero	1.6871	.24418		
S1_6	45.956	94.313	54.900	18.144	4.1805	zero	1.6123	.24153		
S1_7	45.726	94.313	54.900	18.235	4.1805	zero	1.6123	.24153		
S2_0	232.79	453.85	49.471	4.1448	91.942	zero	1.7343	.24778		5.4285
S2_1	230.46	453.85	49.471	4.1866	91.942	zero	1.7343	.24778		
S2_4	225.85	1113.6	49.471	5.6064	262.09	zero	1.8740	.26819		
S2_5	223.59	1113.6	49.471	5.6631	262.09	zero	1.8740	.26819		
S3_0	221.36	2532.2	50.575	8.0643	701.68	.02231	2.1007	.31502		
S3_1	216.73	2500.0	51.486	8.3319	690.89	.02191	2.0965	.31420	.91133	
S5_0	82.25	1997.0	51.486	19.978	534.88	.02191	2.0388	.30565		
S5_05	82.425	1927.5	54.235	20.745	512.43	.02077	2.0280	.30336	2.7487	
S5_1	82.425	1927.5	54.235	20.745	512.43	.02077	2.0280	.30336		
S6_0	15.470	1187.0	56.003	94.796	294.01	.02011	1.9178	.28349	1.7685	
S7_0	14.696	638.55	56.003	81.491	143.71	.02011	1.8071	.26426		

 Compressor: LPC
 Prss Ratio 3.240 Ref Airflw 54.90
 Adiabc Eff .8730 Polytr Eff .8919
 Del h/thet 57.09 Del T/T .4539
 Phys Speed n/a Ref Speed n/a
 % Ref Spd n/a (Refnce N n/a)
 Power Required 4434.
 Clearance n/a Reynold's n/a
 Beta zero
 GV Angle zero GV Dlt Sch zero
 CS SM (1) n/a CA SM (1) n/a

 Intercooler: LPC Cooler
 Heat Trans 2666. Effectvnss .8500
 Temperatures Entrance Exit
 Engine Flow 294.419 94.3129
 Coolant Flow 59.0000 107.560
 Heat Trans Type: Effectiveness Inp
 Press Loss: User Input
 Pressure Loss .03000

 Duct Name Press Loss
 IC_Inlet .0050
 IC_Exit .0050
 Recup_Inlet .0100
 Recup_Exit .0100
 Burn-HPT .0200
 HPT_Blade_Bleed zero
 HPT-PWT zero

 Compressor: HPC
 Prss Ratio 5.091 Ref Airflw 18.24
 Adiabc Eff .8985 Polytr Eff .9184
 Del h/thet 82.17 Del T/T .6490
 Phys Speed n/a Ref Speed n/a
 % Ref Spd n/a (Refnce N n/a)
 Power Required 6817.
 Clearance n/a Reynold's n/a
 Beta zero
 GV Angle zero GV Dlt Sch zero
 CS SM (1) n/a CA SM (1) n/a

 Recuperator: Recup
 Heat Trans 8418. Effectvnss .9000
 Temperatures Entrance Exit
 Core Flow 453.850 1113.64
 Exhaust Flow 1186.95 638.545
 Heat Trans Type: Effectiveness Inp
 Press Loss Data Core Exhaust
 Press Loss Type: Input Input
 Pressure Loss .020000 .050000

 Combustor: Burner
 Exit Temp 2532.2
 Fuel Flow 3974. Fuel/Air .0223
 Efficiency .9900 Press Loss .0100
 Press Loss: User Input
 Fuel Type: User Input
 Fuel LHV 20610 Fuel HCR .3200

 Turbine: HPT
 Prss Ratio 2.632 Ref Airflw 8.332
 Efficiency .8670
 Rfrd Torq n/a Dlt h/thet 27.34
 Phys Speed n/a Ref Speed n/a
 % Ref Spd n/a (Refnce N n/a)
 Power Dlvr 11364 Work Coeff zero
 Clearance n/a Reynold's n/a
 Limit Loading n/a

 Turbine: Power_Turbine
 Prss Ratio 5.328 Ref Airflw 20.75
 Efficiency .9130
 Rfrd Torq n/a Dlt h/thet 46.02
 Phys Speed n/a Ref Speed n/a
 % Ref Spd n/a (Refnce N n/a)
 Power Dlvr 16255 Work Coeff zero
 Clearance n/a Reynold's n/a
 Limit Loading n/a

 Efficiency Type: Adiabatic Efficiency
 Prss Ratio Calc Uses: Exit Pstatc
 (Balancing Turbine)

 Efficiency Type: Adiabatic Efficiency
 Prss Ratio Calc Uses: Exit Pstatc
 (Balancing Turbine)

A.3 ATS Conventional Two Spool

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-----
Ambient: Engine Ambient
Amb Temp 59.000 Amb Press 14.696
Rel Humid 60.0% Spec Humid .00634
Day: User Input Altitude zero
Temp Adder zero Press Adder zero
-----
Overall Performance
Total HP Output 16092.0
Tot Fuel 4096.6 Heat Rate 84.43M
Fuel SFC .25457 H.R. SFC 5.247k
Over Eff .48496 Spec SHP 277.78
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Compressor/Turbine Name	Refrd AirFlow	Press Ratio	Adiab Eff	Polyt Eff	Power	Physcl Speed	Refrd Speed	Refrnc Speed	Pct Ref Speed
LPC	57.931	3.2400	.90600	.92000	4508.6	n/a	n/a	n/a	n/a
HPC	19.220	5.0910	.89175	.91300	7230.7	n/a	n/a	n/a	n/a
HPT	8.4446	1.7972	.87000		7303.8	n/a	n/a	n/a	n/a
LPT	15.033	1.4739	.87500		4554.1	n/a	n/a	n/a	n/a
Power_Turbine	22.162	5.2144	.89900		16255.	n/a	n/a	n/a	n/a

Station Name	Total Press	Total Temp	Physcl Flow	Rfrd Flow	Total Enthalp	Fuel Air Ratio	Entrpy BTU/lR	Heat Capcty BTU/lR	Bleed In	Bleed Out
	psia	deg F	lbm/s	lbm/s	BTU/lb				lbm/s	lbm/s
S0	14.696	59.000	n/a	n/a	-4.344	zero	1.5964	.24129		
S1_0	14.696	59.000	57.931	57.931	-4.344	zero	1.5964	.24129		
S1_3	47.615	285.91	57.931	21.437	50.663	zero	1.6844	.24402		
S1_4	47.377	285.91	57.931	21.545	50.663	zero	1.6844	.24402		
S1_6	45.956	93.036	57.931	19.124	3.8721	zero	1.6118	.24152		
S1_7	45.726	93.036	57.931	19.220	3.8721	zero	1.6118	.24152		
S2_0	232.79	454.46	50.163	4.2041	92.092	zero	1.7345	.24780		7.7675
S2_1	230.46	454.46	50.163	4.2466	92.092	zero	1.7345	.24780		
S2_4	225.85	1086.7	50.163	5.6359	254.87	zero	1.8693	.26740		
S2_5	223.59	1086.7	50.163	5.6928	254.87	zero	1.8693	.26740		
S3_0	221.36	2530.7	51.301	8.1780	701.81	.02268	2.1013	.31532		
S3_1	216.93	2500.0	52.183	8.4446	691.50	.02229	2.0973	.31454	.88171	
S4_0	120.71	2183.0	52.183	14.341	592.58	.02229	2.0619	.30944		
S4_05	120.71	2095.0	55.371	14.961	563.76	.02098	2.0490	.30678	3.1878	
S4_1	120.71	2085.3	55.741	15.033	560.63	.02084	2.0476	.30649	.37018	
S5_0	91.894	1895.8	55.741	21.316	502.88	.02084	2.0240	.30275		
S5_05	81.894	1854.6	57.588	21.829	489.71	.02016	2.0175	.30135	1.8471	
S5_1	80.665	1854.6	57.588	22.162	489.71	.02016	2.0175	.30135		
S6_0	15.470	1156.9	59.069	99.067	285.24	.01964	1.9119	.28223	1.4807	
S7_0	14.696	651.51	59.069	86.457	147.01	.01964	1.8096	.26447		

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-----
Compressor: LPC
Prss Ratio 3.240 Ref Airflw 57.93
Adiabc Eff .9060 Polytr Eff .9200
Del h/thet 55.01 Del T/T .4375
Phys Speed n/a Ref Speed n/a
% Ref Spd n/a (Refnce N n/a)
Power Required 4509.
Clearance n/a Reynold's n/a
Beta zero
GV Angle zero GV Dlt Sch zero
CS SM (1) n/a CA SM (1) n/a
-----

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-----
Intercooler: LPC_Cooler
Heat Trans 2711. Effectvnss .8500
Temperatures Entrance Exit
Engine Flow 285.908 93.0362
Coolant Flow 59.0000 105.791
Heat Trans Type: Effectiveness Inp
Press Loss: User Input
Pressure Loss .03000
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-----
Duct Name Press Loss
IC_Inlet .0050
IC_Exit .0050
Recup_Inlet .0100
Recup_Exit .0100
Burn-HPT .0200
HPT_Blade_Bleed zero
HPT-LPT zero
LPT_Blade_Bleed zero
LPT-PT .0150
-----

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-----
Compressor: HPC
Prss Ratio 5.091 Ref Airflw 19.22
Adiabc Eff .8918 Polytr Eff .9130
Del h/thet 82.79 Del T/T .6539
Phys Speed n/a Ref Speed n/a
% Ref Spd n/a (Refnce N n/a)
Power Required 7231.
Clearance n/a Reynold's n/a
Beta zero
GV Angle zero GV Dlt Sch zero
CS SM (1) n/a CA SM (1) n/a
-----

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-----
Recuperator: Recup
Heat Trans 8165. Effectvnss .9000
Temperatures Entrance Exit
Core Flow 454.456 1086.66
Exhaust Flow 1156.91 651.510
Heat Trans Type: Effectiveness Inp
Press Loss Data Core Exhaust
Press Loss Type: Input Input
Pressure Loss .020000 .050000
-----

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-----
Combustor: Burner
Exit Temp 2530.7
Fuel Flow 4097. Fuel/Air .0227
Efficiency .9900 Press Loss .0100
Press Loss: User Input
Fuel Type: User Input
Fuel LHV 20610 Fuel HCR .3200
-----

```

```

-----
Turbine: HPT
Prss Ratio 1.797 Ref Airflw 8.445
Efficiency .8700
Rfrd Torq n/a Dlt h/thet 17.34
Phys Speed n/a Ref Speed n/a
% Ref Spd n/a (Refnce N n/a)
Power Dlvr 7304. Work Coeff zero
Clearance n/a Reynold's n/a
Limit Loading n/a
-----

```

```

-----
Turbine: LPT
Prss Ratio 1.474 Ref Airflw 15.03
Efficiency .8750
Rfrd Torq n/a Dlt h/thet 11.77
Phys Speed n/a Ref Speed n/a
% Ref Spd n/a (Refnce N n/a)
Power Dlvr 4554. Work Coeff zero
Clearance n/a Reynold's n/a
Limit Loading n/a
-----

```

```

-----
Turbine: Power Turbine
Prss Ratio 5.214 Ref Airflw 22.16
Efficiency .8990
Rfrd Torq n/a Dlt h/thet 44.71
Phys Speed n/a Ref Speed n/a
% Ref Spd n/a (Refnce N n/a)
Power Dlvr 16255 Work Coeff zero
Clearance n/a Reynold's n/a
Limit Loading n/a
-----

```

```

Efficiency Type: Adiabatic Effcnry
Prss Ratio Calc Uses: Exit Pstatc
(Balancing Turbine)

```

```

Efficiency Type: Adiabatic Effcnry
Prss Ratio Calc Uses: Exit Pstatc
(Balancing Turbine)

```

```

Efficiency Type: Adiabatic Effcnry
Prss Ratio Calc Uses: Exit Pstatc
(Balancing Turbine)

```

ATS Advanced Two Spool

Ambient: Engine Ambient				Overall Performance						
Amb Temp	59.000	Amb Press	14.696	Total HP Output 16092.0						
Rel Humid	60.0%	Spec Humid	.00634	Tot Fuel	3973.5	Heat Rate	81.89M			
Day: User Input	Altitude	zero		Fuel SFC	.24692	H.R. SFC	5.089k			
Temp Adder	zero	Press Adder	zero	Over Eff	.49998	Spec SHP	291.50			
Compressor/Turbine	Refrd	Press	Adiab	Polyt	Power	Physcl	Refrd	Refrnc	Pct Ref	
Name	AirFlow	Ratio	Eff	Eff		Speed	Speed	Speed	Speed	
LPC	55.204	3.2400	.90600	.92000	4296.4	n/a	n/a	n/a	n/a	
HPC	18.240	5.0910	.89174	.91300	6834.4	n/a	n/a	n/a	n/a	
HPT	8.2282	1.7555	.87700		6903.5	n/a	n/a	n/a	n/a	
LPT	14.224	1.4569	.88200		4339.8	n/a	n/a	n/a	n/a	
Power_Turbine	20.673	5.4010	.90900		16255.	n/a	n/a	n/a	n/a	
Station	Total	Total	Physcl	Rfrd	Total	Fuel	Entrpy	Heat	Bleed	
Name	Press	Temp	Flow	Flow	Enthlp	Air		Capcty	In	
	psia	deg F	lbm/s	lbm/s	BTU/lb	Ratio	BTU/lR	BTU/lR	lbm/s	
S0	14.696	59.000	n/a	n/a	-4.344	zero	1.5964	.24129		
S1_0	14.696	59.000	55.204	55.204	-4.344	zero	1.5964	.24129		
S1_3	47.615	285.91	55.204	20.428	50.663	zero	1.6844	.24402		
S1_4	47.377	285.91	55.204	20.531	50.663	zero	1.6844	.24402		
S1_6	45.956	88.498	55.204	18.149	2.7761	zero	1.6098	.24149		
S1_7	45.726	88.498	55.204	18.240	2.7761	zero	1.6098	.24149		
S2_0	232.79	447.14	48.901	4.0819	90.279	zero	1.7325	.24761	6.3030	
S2_1	230.46	447.14	48.901	4.1232	90.279	zero	1.7325	.24761		
S2_4	225.85	1093.6	48.901	5.5065	256.74	zero	1.8706	.26761		
S2_5	223.59	1093.6	48.901	5.5621	256.74	zero	1.8706	.26761		
S3_0	221.36	2530.1	50.005	7.9706	701.44	.02257	2.1010	.31521		
S3_1	216.93	2500.0	50.845	8.2282	691.34	.02219	2.0971	.31445	.84021	
S4_0	123.58	2192.5	50.845	13.673	595.38	.02219	2.0628	.30952		
S4_05	123.58	2119.0	53.390	14.157	571.30	.02111	2.0521	.30733	2.5444	
S4_1	123.58	2109.3	53.743	14.224	568.15	.02097	2.0507	.30704	.35276	
S5_0	84.824	1922.3	53.743	19.954	511.07	.02097	2.0277	.30340		
S5_05	84.824	1886.2	55.264	20.363	499.49	.02038	2.0220	.30219	1.5215	
S5_1	83.551	1886.2	55.264	20.673	499.49	.02038	2.0220	.30219		
S6_0	15.469	1165.5	56.308	94.688	287.87	.01999	1.9139	.28273	1.0441	
S7_0	14.696	637.14	56.308	81.882	143.31	.01999	1.8066	.26415		
Compressor: LPC			Intercooler: LPC Cooler				Duct			
Prss Ratio	3.240	Ref Airflw	55.20	Heat Trans	2644.	Effectvnss	.8700	Name	Press	
Adiabc Eff	.9060	Polytr Eff	.9200	Temperatures	Entrance	Exit		IC_Inlet	Loss	
Del h/thet	55.01	Del T/T	.4375	Engine Flow	285.908	88.4980		IC_Exit	.0050	
Phys Speed	n/a	Ref Speed	n/a	Coolant Flow	59.0000	106.887		Recup_Inlet	.0100	
% Ref Spd	n/a	(Refnce N	n/a)	Heat Trans Type: Effectiveness	Inp			Recup_Exit	.0100	
Power Required	4296.			Press Loss: User Input				Burn-HPT	.0200	
Clearance	n/a	Reynold's	n/a	Pressure Loss	.03000			HPT_Blade_Bleed	zero	
Beta	zero							HPT-LPT	zero	
GV Angle	zero	GV Dlt Sch	zero					LPT_Blade_Bleed	zero	
CS SM (1)	n/a	CA SM (1)	n/a					LPT-PT	.0150	
Compressor: HPC			Recuperator: Recup				Combustor: Burner			
Prss Ratio	5.091	Ref Airflw	18.24	Heat Trans	8140.	Effectvnss	.9000	Exit Temp	2530.1	
Adiabc Eff	.8917	Polytr Eff	.9130	Temperatures	Entrance	Exit		Fuel Flow	3973.	
Del h/thet	82.79	Del T/T	.6542	Core Flow	447.137	1093.64		Fuel/Air	.0226	
Phys Speed	n/a	Ref Speed	n/a	Exhaust Flow	1165.48	637.140		Efficiency	.9900	
% Ref Spd	n/a	(Refnce N	n/a)	Heat Trans Type: Effectiveness	Inp			Press Loss: User Input		
Power Required	6834.			Press Loss Data	Core	Exhaust		Fuel Type: User Input		
Clearance	n/a	Reynold's	n/a	Press Loss Type: Input	Input	Input		Fuel LHV	20610	
Beta	zero			Pressure Loss	.020000	.050000		Fuel HCR	.3200	
GV Angle	zero	GV Dlt Sch	zero							
CS SM (1)	n/a	CA SM (1)	n/a							
Turbine: HPT			Turbine: LPT				Turbine: Power_Turbine			
Prss Ratio	1.755	Ref Airflw	8.228	Prss Ratio	1.457	Ref Airflw	14.22	Prss Ratio	5.401	
Efficiency	.8770			Efficiency	.8820			Ref Airflw	20.67	
Rfrd Torq	n/a	Dlt h/thet	16.82	Rfrd Torq	n/a	Dlt h/thet	11.52	Rfrd Torq	n/a	
Phys Speed	n/a	Ref Speed	n/a	Phys Speed	n/a	Ref Speed	n/a	Dlt h/thet	45.96	
% Ref Spd	n/a	(Refnce N	n/a)	% Ref Spd	n/a	(Refnce N	n/a)	Phys Speed	n/a	
Power Dlvr	6903.	Work Coeff	zero	Power Dlvr	4340.	Work Coeff	zero	% Ref Spd	n/a	
Clearance	n/a	Reynold's	n/a	Clearance	n/a	Reynold's	n/a	Power Dlvr	16255	
Limit Loading	n/a			Limit Loading	n/a			Work Coeff	zero	
								Clearance	n/a	
								Reynold's	n/a	
								Limit Loading	n/a	
Efficiency Type: Adiabatic Efficiency			Efficiency Type: Adiabatic Efficiency			Efficiency Type: Adiabatic Efficiency				
Prss Ratio Calc Uses: Exit Pstatc			Prss Ratio Calc Uses: Exit Pstatc			Prss Ratio Calc Uses: Exit Pstatc				
(Balancing Turbine)			(Balancing Turbine)			(Balancing Turbine)				

APPENDIX B

First-Cut Temperature Estimates for Candidate ATS Materials

ENGINEERING DESIGN MEMO

PROJECT:	Advanced Turbine System	TITLE :	First-Cut Temperature Estimates for Candidate ATS Materials	SECTION:	C.1-1
PART:	II			PAGE:	45 of 6
ORIGINATOR:	M. Fitzpatrick	DATE :	3/29/94	REVISION:	A

In order to perform more detailed cycle/cooling analyses for the ATS program, a need has been expressed to provide estimated maximum component operating temperatures for various candidate materials. The preferred approach for making such an estimate is to look at each component in the context of the engine system, and take into account the operating circumstances and environmental conditions which are critical. All of these details are obviously not yet available for the ATS engine. Therefore, fairly broad assumptions are required about the various components, which potentially could make the estimates less accurate than desired.

There are a minimum of two assumptions required to make a first-cut temperature estimate for a given component; the design life of the part, and the critical operating stress. Design Engineering provided the estimated component stress levels, and the guideline provided for life in this initial analysis was 8000 hours. Tables 1 through 6 summarize the results of this effort, categorized by component type. Temperature estimates were reported for both strength-related limits, and for recommended oxidation limits. For the oxidation-related limits, various coatings are considered for the metallic material candidates. The turbine blade stress level assumptions are based on "conventional" materials, thus ceramic blades may actually have lower CF stresses than stated here.

Be aware that the temperature estimates are based on average, or typical data and do not reflect design minimums. In general, the stress-limited temperature estimates were related to rupture strength of the material since details of the cyclic fatigue environment were not available. Additional analysis taking into account fatigue is required, particularly for the turbine disk applications.

The candidate materials range from technologies which are currently available, to ones that are anticipated to be available in the 3-5 year timeframe of the planned ATS materials development effort. The last column of each table provides an estimated timeframe when the material (or coating) may be available for use on ATS.

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TABLE 1. CANDIDATE BLADE MATERIALS FOR ATS

ASSUMPTION: LIFE OF 8000 HOURS TO BE ASSUMED IN THIS FIRST CUT

COMPONENT TYPE	CANDIDATE MATERIALS	POTENTIAL COATINGS	OXIDATION LIMITED TEMP	ASSUMED STRESS	STRESS LIMITED TEMP ^a	MATERIAL AVAILABILITY
BLADES	Equiaxed MM247	Pt-Aluminide CVD/VPS MCrAlY PdCrSi ALUMINIDES MCrAlY + TBC ¹	1850 F 1900 F 2000 F 2150 F	30 KSI	1575 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	DS CM247LC	Pt-Aluminides CVD/VPS MCrAlY PdCrSi Aluminide Pt-Al or MCrAlY + TBC ¹	1900 F 1950 F 2000 F 2150 F	30 KSI	1620 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	DS CM186LC	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide MCrAlY + TBC ¹	1900 F 1950 F 2000 F 2150 F	30 KSI	1650 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	CMSX-4 LS ⁴	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide Pt-Al or MCrAlY + TBC ¹	1950 F 1975 F 2000 F 2150 F	30 KSI	1700 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	SILICON NITRIDE	-	2300 F ⁵	30 KSI	2200 F	1-2 YEARS
	MA 8000 (ODS ALLOY)	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide MCrAlY + TBC ¹	1975 F 2000 F 2025 F 2175 F	30 KSI	1880 F	1-2 YEARS 1-2 YEARS 1-3 YEARS 2-4 YEARS

NOTES: 1. TBC = THERMAL BARRIER COATING. TBCs CREATE A THERMAL GRADIENT WHEREIN THE UNDERLYING METAL OPERATES 150-200 F LOWER THAN THE SURFACE OF THE COMPONENT (IE, GAS TEMPERATURE). TBCs REQUIRE BACK-SIDE COOLING IN ORDER TO SET UP THE THERMAL GRADIENT, THUS SOLID AIRFOILS WOULD NOT BE ACCEPTABLE FOR TBCs.

2. NEEDS TO BE VERIFIED IN THE HIGH GAS VELOCITY, HIGH GAS PRESSURE ENVIRONMENT OF A TURBINE.

3. APPLYING TBCs TO ODS ALLOYS ASSUMES THE DEVELOPMENT OF HOLLOW COMPONENTS TO PROVIDE PASSAGES FOR BACK-SIDE COOLING. SINCE THE ODS ALLOYS ARE NOT CASTABLE, THE PASSAGES WOULD MOST LIKELY BE CREATED AS A BRAZE/DIFFUSION BONDED ASSEMBLY OF MULTIPLE PIECES.

4. LS = LOW SULFUR VERSION OF CMSX-4 WITH IMPROVED OXIDATION RESISTANCE.

5. BULK MATERIAL TEMPERATURE.

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TABLE 2. CANDIDATE TURBINE DISK MATERIALS FOR ATS

ASSUMPTION: LIFE OF 8000 HOURS TO BE ASSUMED IN THIS FIRST CUT.

COMPONENT TYPE	CANDIDATE MATERIALS	ASSUMED LUG STRESS	STRESS LIMITED TEMP	MATERIAL AVAILABILITY
TURBINE DISKS ¹	ALLOY 718	30 KSI	1200 F	CURRENT
	WASPALLOY	30 KSI	1350 F	CURRENT
	UDIMET 720, FINE GRAIN	30 KSI	1375 F	CURRENT
	UDIMET 720, COARSE GRAIN	30 KSI	1450 F	1-2 YEARS
	DUAL-ALLOY: UDIMET 720 + MAR M 247 RIM	30 KSI	1575 F	2-3 YEARS
	CARBON-CARBON	30 KSI	3000 F	3-8 YEARS
	CARBON-SIC	30 KSI	2300 F	3-8 YEARS
	CFCC	30 KSI	2300-2500F	3-8 YEARS

NOTES:

THIS TABLE ADDRESSES ONLY THE REQUIRED RIM PROPERTIES OF THE TURBINE DISK, IE. CREEP-RUPTURE PROPERTIES ONLY. DESIGN ENGINEERING COULD NOT PROVIDE A PREDICTION OF THE CYCLIC STRESSES/STRAINS IMPOSED ON THE DISK. THEREFORE, SIGNIFICANT WORK REMAINS IN THE AREA OF LOW CYCLE FATIGUE, CRACK GROWTH AND FRACTURE SPECS.

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TABLE 3. CANDIDATE NOZZLE MATERIALS FOR ATS

ASSUMPTION: LIFE OF 8000 HOURS TO BE ASSUMED IN THIS FIRST CUT.

COMPONENT TYPE	CANDIDATE MATERIALS	POTENTIAL COATINGS	OXIDATION LIMITED TEMP	ASSUMED STRESS ^a	STRESS LIMITED TEMP	MATERIAL AVAILABILITY
NOZZLES	Equiaxed MM247	Pt-Aluminide CVD/VPS MCrAlY PdCrSi ALUMINIDES MCrAlY + TBC ¹	1850 F 1800 F 2000 F 2150 F	25 KSI	1575 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	DS CM247LC	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide Pt-Al or MCrAlY + TBC ¹	1800 F 1850 F 2000 F 2150 F	25 KSI	1620 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	DS CM186LC	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide MCrAlY + TBC ¹	1800 F 1850 F 2000 F 2150 F	25 KSI	1650 F	CURRENT CURRENT 1-3 YEARS 2-4 YEARS
	CMSX-4 LS	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide Pt-Al or MCrAlY + TBC ¹	1850 F 1875 F 2000 F 2150 F	25 KSI	1700 F	1-2 YEARS 1-2 YEARS 1-3 YEARS 2-4 YEARS
	SILICON CARBIDE	-	2400 F ²	25 KSI	2300 F	2-3 YEARS
	SILICON NITRIDE	-	2300 F ²	25 KSI	2300 F	1-2 YEARS
	MA 6000 (ODS ALLOY)	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide MCrAlY + TBC ⁴	1875 F 2000 F 2025 F 2175 F	25 KSI	1880 F	1-2 YEARS 1-2 YEARS 1-3 YEARS 2-4 YEARS
	MA 754 (ODS ALLOY)	Pt-Aluminide CVD/VPS MCrAlY PdCrSi Aluminide MCrAlY + TBC ⁴	1875 F 2000 F 2025 F 2175 F	25 KSI	1750 F	1-2 YEARS 1-2 YEARS 1-3 YEARS 2-4 YEARS

NOTES:

- TBC = THERMAL BARRIER COATING. TBCs CREATE A "THERMAL CIRCUIT" OR THERMAL GRADIENT WHEREIN THE UNDERLYING METAL OPERATES 150-200 F LOWER THAN THE SURFACE OF THE COMPONENT (E GAS TEMPERATURE). TBCs REQUIRE BACK-SIDE COOLING IN ORDER TO SET UP THE THERMAL CIRCUIT, THUS SOLID NOZZLES AIRFOILS WOULD NOT BE ACCEPTABLE.
- NEEDS TO BE VERIFIED IN THE HIGH GAS VELOCITY, HIGH GAS PRESSURE ENVIRONMENT OF A TURBINE.
- TYPICALLY THE LIFE LIMITING FACTOR FOR NOZZLES IS THERMAL-MECHANICAL FATIGUE (TMF) AND OXIDATION. DESIGN ENGINEERING HAD DIFFICULTY PROVIDING A STRESS PREDICTION FOR THIS SITUATION SINCE TMF IS PRIMARILY DRIVEN BY THERMAL GRADIENTS ACROSS THE NOZZLE. THUS, THE ACCURACY OF THE STRESS/TEMP ARE IN QUESTION.
- APPLYING TBCs TO ODS ALLOYS ASSUMES THE DEVELOPMENT OF HOLLOW COMPONENTS TO PROVIDE PASSAGES FOR BACK-SIDE COOLING. SINCE THE ODS ALLOYS ARE NOT CASTABLE, THE PASSAGES WOULD MOST LIKELY BE CREATED BRAZE ASSEMBLY OF MULTIPLE PIECES.
- BULK MATERIAL TEMPERATURE.

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TABLE 4. CANDIDATE LOW THERMAL EXPANSION MATERIALS FOR ATS

ASSUMPTION: LIFE OF 8000 HOURS TO BE ASSUMED IN THIS FIRST CUT.

COMPONENT TYPE	CANDIDATE MATERIALS	POTENTIAL COATINGS	OXIDATION LIMITED TEMP	ASSUMED STRESS	STRESS LIMITED TEMP	MATERIAL AVAILABILITY
DIAPHRAGM, ETC (LOW CTE)	INCOLOY 903	Fe-ALUMINIDES Fe/Cr-ALUMINIDES	1350 F 1600 F	15 KSI	1350 F	CURRENT
	INCOLOY 909	Fe-ALUMINIDES Fe/Cr-ALUMINIDES	1350 F 1600 F	15 KSI	1250 F	CURRENT
	HAYNES 242	NONE	1500 F	15 KSI	1350 F	1-2 YEARS

TABLE 5. CANDIDATE TIP SHOE MATERIALS FOR ATS

ASSUMPTION: LIFE OF 8000 HOURS TO BE ASSUMED IN THIS FIRST CUT.

COMPONENT TYPE	CANDIDATE MATERIALS	POTENTIAL COATINGS	OXIDATION LIMITED TEMP	ASSUMED STRESS	STRESS LIMITED TEMP	MATERIAL AVAILABILITY
TIP SHOES	EQUIAXED MAR M 247	MCrAlY ABRADABLES CERAMICS	1900 F 2000-2200 F	25 KSI	1850 F	CURRENT 2-4 YEARS
	CMSX-4 LS	MCrAlY ABRADABLES CERAMICS	1950 F 2000-2200 F	25 KSI	1800 F	CURRENT 2-4 YEARS
	SILICON NITRIDE	-	2300 F	25 KSI	2300 F	1-3 YEARS
	NZP	-	3000 F	5 KSI	3000 F	2-5 YEARS

NOTES: 1. LS = LOW SULFUR VERSION OF CMSX-4 WITH IMPROVED OXIDATION RESISTANCE.

2. NZP = LOW THERMAL EXPANSION CRYSTALLINE CERAMIC BaZrPSiO

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TABLE 6. CANDIDATE COMBUSTOR SECTION MATERIALS FOR ATS

ASSUMPTION: LIFE OF 8000 HOURS TO BE ASSUMED IN THIS FIRST CUT.

COMPONENT TYPE	CANDIDATE MATERIALS	POTENTIAL COATINGS	OXIDATION LIMITED TEMP	MATERIAL AVAILABILITY
COMBUSTOR	HASTELLOY X	-	1700 F	CURRENT
	HAYNES 230	-	1800 F	CURRENT
	HAYNES 230	TBC	2000 F	1-3 YEARS
	CAST-COOL CMSX-4 LS ¹	PdCrSi Aluminide	2000 F	2-4 YEARS
	CAST-COOL CMSX-4 LS	MCrAlY + TBC	2200 F	3-5 YEARS
	MA 956 (ODS ALLOY)	-	2150 F	CURRENT
	PARTICULATE REINF/AL ₂ O ₃	-	2200 F	3-5 YEARS
	SIC/SIC CFCC	-	2200 F	2-4 YEARS
	AL ₂ O ₃ /AL ₂ O ₃ CFCC ¹	-	2400 F	3-5 YEARS
	AEA SYSTEM 2.2 ³	Note 3	2650 F	3-5 YEARS
	BZP	-	>2500 F	2-4 YEARS
	Altra KVS16 ⁴	-	2700 F	3-5 YEARS

- NOTES:**
1. CAST-COOL TECHNOLOGY PROVIDES ENHANCED SUBSTRATE COOLING WITH REDUCED AIR FLOW. LS = LOW SULFUR VERSION OF CMSX-4 WITH IMPROVED OXIDATION RESISTANCE.
 2. SILICON FIBER REINFORCED GLASS-CERAMIC.
 3. AEA, INC. PROPRIETARY SEAL COAT.
 4. BZP = LOW THERMAL EXPANSION CRYSTALLINE CERAMIC BaZrPbSiO.
 5. ALTRA KVS16 IS SUPPLIED BY INTERNATIONAL THERMOPRODUCTS, INC.

APPENDIX C

Glossary

ATS	Advanced Turbine System. A gas turbine-based energy conversion system as defined To the U. S. Congress by the U. S. Department of Energy (DOE). An ATS is distinguished from current gas turbines by markedly increased thermal efficiency, reliability, availability and maintainability and by decreased exhaust emissions and cost of power produced.
ATS50	Solar's designation for an ATS designed to meet the contract goal of 50 percent thermal efficiency.
ATS60	Solar's designation for an ATS designed to meet a "stretch" goal of 60 percent thermal efficiency.
BZP	Barium Zirconium Phosphate. A family of materials whose composition can be tailored to result in low, or zero, coefficient of thermal expansion. It is resistant to thermal shock, and is stable to 1200°C.
CFATS	Coal-Fired Advanced Turbine System.
CFCC	Continuous Fiber-Reinforced Ceramic Composite. A high temperature composite material which consists of a ceramic matrix reinforced with fabric, tape, or rows of a high modulus fiber. CFCC's are typically not as flaw sensitive as monolithic ceramics, and can be fabricated into large parts such as combustion chambers.
CHORD	The axial length of an airfoil measured along a line drawn tangent to the leading- and trailing-edge radii. Chord is the characteristic dimension used in scaling of airfoils.
CSGT	Ceramic Stationary Gas Turbine. A DOE-funded program contracted to Solar Turbines Incorporated. The program goal is to demonstrate improved performance of a production gas turbine by retrofitting key components with ceramic counterparts for a 4000-hour field test.
EFFECTIVENESS	(ϵ_R for recuperator, ϵ_i for intercooler). A characteristic of a heat exchanger -- the ratio of the amount of heat transferred to the total heat available in the hot fluid between its entry temperature and the entry temperature of the cold fluid.
EFFICIENCY, COMPRESSOR	(η_c) Ratio of the work imparted to the air flow to the total work input. Unless otherwise specified, "adiabatic" efficiency (subscr. - ad) is implied, i.e., flow conditions at both inlet and outlet are in terms of absolute, or total, pressure and temperature. "Polytropic" efficiency (subscr. - p) is the theoretical efficiency of a very large number of identical low pressure-ratio stages and essentially normalizes pressure ratio for comparison of differing compressors.
EFFICIENCY, THERMAL	(η_{th}) Also termed cycle efficiency. The ratio of energy input to energy output from a gas turbine. Unless specifically designated otherwise, thermal efficiency of an ATS will be defined on the basis of net power output from the turbine shaft.

EFFICIENCY, TURBINE	(η). Ratio of the work produced by a turbine to the work it extracts from the gas flow. When applied to a GP turbine, total-to-total efficiency is implied, this definition being based on total or absolute inlet and exit conditions. When applied to a power turbine, total-to-static efficiency is implied, thus accounting for static pressure recovery as a result of kinetic energy conversion in the exhaust diffuser.
FGM	Functionally Graded Material. A multilayer material or coating system with each layer graded to provide different properties at the surface of the component relative to the core or substrate. An illustrative example would be a turbine tip-shroud with a top coating tailored for abradability, an intermediate layer designed for oxidation resistance, and a substrate tailored for high strength.
GAS PRODUCER	(Abbr. GP) An element, or module, of a gas turbine which is required to provide a hot gas stream capable of propelling a power output turbine or other energy conversion device. As a minimum it consists of a compressor, a combustor, a turbine and associated shafting. Each of these components, in turn, may be of any of several types and may consist of one or more stages.
GPT	Gas Producer Turbine. May include HP and LP turbines.
GFATS	Gas-Fired Advanced Turbine System.
GP	See GAS PRODUCER.
HIP	Hot Isostatic Pressing. A process for simultaneously heating a component, or powder metallurgy compact while subjecting it to isostatic pressure using an inert gas atmosphere. The temperature and pressure area are high enough to produce densification of the materials.
HP	High Pressure. This prefix is used to designate an individual section of a series pair of aerodynamic components operating in the high pressure regime of the two. HPC designates the high pressure compressor and HPT designates the high pressure turbine of an HP, or high pressure, spool.
INTERCOOLER	A heat exchanger placed between stages of compression in a gas turbine in order to remove heat from the compression air thereby reducing the temperature of air going to and through the succeeding stage(s).
LP	Low Pressure. This prefix is used to designate the individual of a series pair of aerodynamic components operating in the lower pressure regime of the two. LPC designates the low pressure compressor and LPT designates the low pressure turbine of an LP, or low pressure, spool.

MCrAlY	A designation for an overlay coating applied to superalloy turbine components for increased oxidation and corrosion resistance. "McCrAlY" is derived from the elemental constituents of the coating i.e., Cr = Chromium, Al = Aluminum, Y = Yttrium M = Ni Fe or Co (depending on substrate).
PATTERN FACTOR	(Abbr. PF). A parameter defining the range of temperatures extant in the exit gas flow from a gas turbine combustor. $PF = \frac{T_{MAX\ EX} - T_{AVG\ EX}}{T_{AVG\ EX} - T_{AVG\ INLET}}$
	All temperatures are absolute.
PF	See PATTERN FACTOR.
PITCH	The circumferential distance between two adjacent airfoils in an axial turbomachinery annulus. It is equal to 2 times pi times the radius from the annulus centerline to the subject airfoil divided by the number of airfoils in the annulus.
POWER TURBINE	(Abbr. PT). A turbine stage in a gas turbine whose work output is used solely to drive the load with none being used by the compressor. In a 2-shaft gas turbine, the power turbine is fixed to a separate shaft from that of the GP turbine. It is normally – but not required to be – the last, or lowest pressure, turbine stage.
PR	Pressure Ratio. For a compressor or compressor stage, the ratio of outlet to inlet total pressure. For a turbine or turbine stage, the ratio of inlet to outlet total pressure.
PROFILE	The distribution of gas temperature within a single radial plane of a gas turbine combustor exit or other downstream annulus. The temperature profile represents the environment experienced by a turbine blade as it rotates through a temperature <u>pattern</u> thus averaging out circumferential variations. A "Profile Factor" can be defined using the Pattern Factor equation but confining the temperature data to a single radial plane.
PSR	Primary Surface Recuperator. Solar's proprietary design in which all heat exchange surfaces are "primary," i.e., transferring heat in their transverse direction. (A "secondary" surface, such as a fin, transfers heat in a lateral direction).
PT	See POWER TURBINE.
RECUPERATOR	A heat exchanger placed in the exhaust gas stream of a gas turbine in order to extract heat from the exhaust gases and return it to the cycle by heating the combustor inlet air. The term "recuperator" designates a static device as opposed to a "regenerator" which is a periodic device.

SHROUDED	A type of turbine blade design. A "shrouded" turbine features a short circumferential shroud segment attached to each blade tip. Together, these segments make up a full circular, rotating shroud. The outside surface of this shroud normally carries one or more circumferential seal elements. Conversely, a "non-shrouded" turbine is characterized by open blade tips rotating in close proximity to a stationary shroud.
SPOOL	The compression and expansion element of a gas producer, consisting of a compressor, a turbine and associated shafting. The turbine is designed so as to provide the amount of work required for the compression process plus any mechanical losses. A gas producer includes one or more spools and will be designated as 1-spool, 2-spool, etc.
STALL	A condition arising in one or more stages of an axial compressor in which the design pressure-velocity-rotational speed relationship is disrupted such that separation of the air flow from the blade contour occurs.
STAGE WORK FACTOR	The ratio of work actually performed by a flow of cooling air within a turbine stage, to that possible if the flow were added to the hot gas stream.
SURGE	The condition occurring when a compressor is operated below its minimum stable air flow rate for a given rotational speed. Surge is characterized by cyclic backflow of air in the flowpath accompanied by violent pressure fluctuations. During surge all stages of the compressor will be in a stall condition.
TBC	<u>T</u> hermal <u>B</u> arrier <u>C</u> oating. A thermally insulating ceramic coating (ZrO_2) applied to superalloy combustor and airfoil components. The insulative properties of the coating allow increased turbine inlet temperatures while maintaining acceptable metal substrate temperatures.
TRIT	<u>T</u> urbine <u>R</u> otor <u>I</u> nlet <u>T</u> emperature. The average gas temperature entering the rotor annulus of the first turbine stage in a gas turbine. It is less than the average combustor exit temperature due to the mixing of spent cooling air flow from upstream sources, primarily the first stage nozzle vanes.
ZWEIFEL COEFFICIENT	A measure of turbine blade loading based on pitch/chord ratio and gas turning angle as independent variables.

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