AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

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

**Quarterly Report
November 1993 - January 1994**

K. W. Karstensen

June 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

MASTER

ds
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, 175 Oak Ridge Turnpike, Oak Ridge, TN 37831; prices available at (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

INTRODUCTION

This Quarterly Technical Progress Report covers the period November 1, 1993, through January 31, 1994, for Phase II of the Advanced Turbine Systems (ATS) Program by Solar Turbines Incorporated under DOE Contract No. DE-AC421-93MC30246. The objective of this program is to provide the conceptual design and product development plan for an industrial gas turbine system to operate at a thermal efficiency of 50 percent ("ATS50") with future improvement to 60 percent ("ATS60").

During the prior quarter Solar's ATS Engine Design Team characterized the intercooled and recuperated (ICR) gas turbine cycle in 1-spool, 2-shaft, and 2-spool 3-shaft arrangements. Fixed and variable geometry free power turbines were compared in both arrangements and sensitivity of all combinations to component performance was determined. Full- and part-load performance were compared over a range of ambient air temperatures.

During the quarter just completed, the Team defined four unique and different physical arrangements of the gas turbine components outlined above. These three arrangements were then examined in terms of their ability to support Program goals of thermal efficiency, low emissions, increased reliability, availability and maintainability (RAM), and reduced cost of electrical power production. The computer model of the ICR gas turbine cycle was refined to more accurately define the re-entry of spent cooling air to the turbine flowpath. This work, together with preliminary specification of component cooling needs, suggested that earlier studies of the pressure ratio/firing temperature/thermal efficiency relationship should be re-visited. This accomplished, the effect of total cooling air bleed requirements on thermal efficiency was determined. This will lead to the selection of hot section material capability/cooling air requirements which are able to meet Program goals.

As noted in the first quarterly report, where there is apparently conflicting data, later results should take precedence due to the continuing refinement of analytical models.

1.0 PROPOSED GFATS COMPONENT ARRANGEMENTS

A study was conducted in which four different gas turbine arrangements, proposed for Solar's Gas Fired Advanced Turbine System (GFATS) engine were compared to determine the operability and part load efficiency of each.

Operability defines the gas turbine's ability to start and run at part power. Thermal efficiency is defined as shaft horsepower output divided by BTU/unit of time provided by the fuel.

The arrangements compared were:

- 1) A conventional 2-spool gas producer arrangement with a free power turbine (Fig. 1a).
- 2) A 1-spool with the same compressors as with the 2-spool gas producer arrangement, but connected on the same shaft to a single turbine (Fig. 1b).
- 3) A 2-spool gas turbine in which the power is extracted from the high pressure turbine, (Figure 1c).
- 4) A 2-spool gas producer arrangement in which the free power turbine is the first turbine following the low emissions combustor, (Figure 1d).

Figure 1a. Conventional 2-Spool Gas Producer With Free Turbine

Figure 1b. 1-Spool Gas Producer With Free Turbine

Figure 1c. 2-Spool Gas Producer With Power Extraction From the HP Turbine

Figure 1d. 2-Spool Gas Producer With Free Turbine as the First Turbine

The results of the study showed that the conventional 2-spool gas producer has no special operability problem. The efficiency of this cycle will be used as a baseline to make comparisons with the other cycles.

The conventional cycle with the 1-spool gas producer has similar efficiency to the 2-spool conventional cycle at high power settings. However, as the power is reduced, the low pressure compressor (LPC) in this arrangement is "pushed" toward surge conditions. To minimize the surge problem, the compressor discharge must be bled. This maintains adequate surge margin, but lowers the part-load efficiencies. The effect is most significant from 67 to 34 percent power. Variable LPC guide vanes can overcome this problem.

The 2-spool high pressure turbine (HPT) power extraction arrangement provides the best part load efficiency. However, the operability concerns are that, firstly, it is essentially a constant speed machine from the viewpoint of the load. Secondly, the low pressure turbine (LPT) and the LPC have differing optimum speeds, probably requiring a gearbox, and the LPT would require variable nozzles to be operable. This arrangement may be difficult to start because the hot combustor gases must pass through and turn the HP/Power Turbine connected to the load in order to reach the LP spool and bring it to self-sustaining speed.

The 2-spool gas producer with the power turbine initially displayed a similar efficiency characteristic to the baseline arrangement. However, the operability of the engine is more complex. It would require variable geometry on both the gas generator turbines, and would also require that the flow be routed around the machine, as with the high pressure spool power extraction arrangement. Also, similar to the previous concept, it would probably require a gearbox between the LPT and LPC to optimize the speed match between the turbine and its compressor. Finally, the engine will be difficult to start because the combustor gases must travel through a static power turbine coupled to the driven equipment to reach the HPT, thus reducing the work available from the hot gases.

These results are summarized in Table 1.

1.1 ASSUMPTIONS AND METHODOLOGY

The methodology used attempted to compare the arrangements on an equal basis, by keeping the component characteristics (efficiencies, flow capacities, pressure losses, etc.) the same. The off-design performance of the compressors and turbines were established by scaling up current hardware performance as to a level achievable by 2000 AD.

The basic design point parameters were:

- Inlet flow 1 (normalized)
- LPC polytropic efficiency - 91.5%
- HPC polytropic efficiency - 91.5%
- Power turbine efficiency 88.84%
- Recuperator effectiveness - 90%
- Recuperator exhaust inlet temperature 1300° F - Maintained by varying the geometry of the last turbine before the recuperator.
- Intercooler effectiveness - 90%
- 6% pressure loss from the HPC discharge to the HPT inlet
- 3% intercooler pressure loss

Table 1. - Comparison of Proposed ATS Arrangements

Engine Type	Part Load Efficiency	Operability
Conventional 2-Spool with Power Turbine	Baseline for Comparison	No special concerns. (All engines have variable nozzles on the last turbine in the cycle to maintain constant recuperator inlet temperature.)
Conventional with 1-Spool Gas Producer	Reduced by bleed for LPC surge margin	<ol style="list-style-type: none"> 1) LPC surge control (bleed or variable guide vanes) 2) Speed mismatch between compressors requires a gear box or a decrease in LPC efficiency.
HP Spool Power Extraction	Best part load efficiency of all arrangements	<ol style="list-style-type: none"> 1) Requires variable LPT geometry for operability (In addition to recuperator inlet temperature control) 2) Requires a gearbox between the LPC and LPT 3) Requires a reversed flowpath, in which the low pressure spool is on the inside, the high pressure spool on the outside. 4) May be difficult to start
HP Power Turbine	Part load efficiency same as conventional 2-spool gas turbine.	<ol style="list-style-type: none"> 1) Requires variable HPT and LPT geometry for operability (in addition to recuperator inlet temperature control). Without it, the HPC speed and TRIT both increase with decreasing load. 2) Requires a gearbox between the LPC and LPT 3) Requires a reversed flowpath, in which the low pressure spool is on the inside, the high pressure spool on the outside. 4) Starting may be very difficult

5% pressure loss in the recuperator hot side.

For two-turbine cycles:

GPT efficiency 89%

For three-turbine cycles:

HPT efficiency 88.23%

LPT efficiency 88.23% (This combination gives approximately 89% overall efficiency for the two turbines).

Burner exit temperature 2507° F. This gives TRIT 2450° F for the three-turbine cycles, and 2432° F for the two-turbine cycles (due to the bleed differences).

Cooling Flow Assumptions

For three-turbine cycles:

3% bleed from the HPC discharge to cool the first turbine (75% stage work factor)

2% bleed from the HPC discharge to cool the second turbine (94% stage work factor)

1% bleed from the HPC discharge to cool the third turbine (94% stage work factor)

For two-turbine cycles:

4% bleed from the HPC discharge to cool the first turbine (75% stage work factor)

2% bleed from the HPC discharge to cool the second turbine (94% stage work factor)

1.2 ARRANGEMENT NO. 1 (FIGURE 1A)

The first arrangement run was the standard 2-spool engine with a free power turbine. This engine has no adverse operability characteristics, and will be the baseline engine to which the other cycles will be compared. See Figure 2.

1.3 ARRANGEMENT NO. 2 (FIGURE 1B)

The second arrangement to be examined was the same cycle as the 2-spool engine, with the high pressure compressor (HPC) and LPC connected to a single turbine on the same shaft. This cycle was proposed as a way to reduce the complexity and cooling requirements of the cycle, by eliminating one of the turbines.

Figure 2. Thermal Efficiency vs. Load for Various GFATS Arrangements

This arrangement demonstrates efficiency comparable to that of the 2-spool conventional cycle at the higher power settings. However, as the load decreases, the LPC tends to move toward surge. At around 60 percent power, without some compensating factor, the LPC goes into surge. In the study, the discharge of the LPT was bled to maintain adequate surge margin. This bleed results in up to a two point reduction in efficiency at 35 percent power, although the difference begins to decrease as the power decreases further, due to the repositioning of the compressors to more efficient operating points. Variable LPC guide vanes can control this surge problem, instead of bleeding. However, it is doubtful that the effect would be strong enough to solve the problem completely. If this cycle is chosen, further study on guide vanes must be conducted.

Beside the requirement for LPC surge control, the only other operability concern is the compressor speeds. By connecting the compressors on a single spool, they must run at the same physical speed, unless gearing is placed between them. It is estimated that this would result in approximately a two percent reduction in the LPC efficiency due to added mechanical loss. This reduction in efficiency must be confirmed in future studies.

1.4 ARRANGEMENT NO. 3 (FIGURE 1C)

The third arrangement involves attaching the HPC and the load to the first turbine following the combustor (the HPT/Power Turbine), and leaving the LPC on its own spool with the LPT. This arrangement showed comparable performance at the design point to the other cycles, but its part load performance improved over the other arrangements. This arrangement is operable, but requires LPT variable nozzles to operate at part load. Its operation is similar to that of a single shaft engine. The speed of the high pressure spool is chosen, and the speed of the low pressure spool is varied to achieve part load performance.

The operability of this arrangement will require a gearbox between the LPT and LPC, because the LPC optimum speed would be much higher than that of the LPT.

1.5 ARRANGEMENT NO. 4 (FIGURE 1D)

The last configuration studied features a free turbine as the first turbine following the combustor. The efficiency of this arrangement at full load is comparable to the other engines. The part load efficiency is very close to the conventional 2-spool arrangement. However, the operability of this engine is more difficult than for the other arrangements.

Firstly, this arrangement would require variable turbine nozzles on both the gas producer turbines. The scheduling of these nozzles would have to be addressed, as the HP spool speed is very sensitive to changes in the LPT nozzle settings. Secondly, as power output is reduced, the setting of the LPT nozzle would have to take into account surge margin of the LPC. The optimum LPT nozzle setting at 33 percent power, for example, could tend to push the LPC too close to surge. Therefore, a tradeoff between thermal efficiency and LPC surge margin would have to be used to determine the LPT nozzle settings.

As with the HP spool power extraction arrangement, this cycle requires a gearbox between the LPC and LPT, as the optimum speeds of the two components are not equal.

Also, this arrangement appears to be very difficult to start, as the minimum self-sustaining HPC speed appears very high when compared to the other engines. If this engine were selected, further studies would have to be made in this area.

2.0 PARAMETRIC STUDY OF PRESSURE RATIO AND TURBINE ROTOR INLET TEMPERATURE (TRIT)

The initial step of this study was to run a set of cycles for a conventional two spool, free power turbine ICR gas turbine with varying turbine inlet temperatures, compressor overall pressure ratios, and work splits between the HP and LP turbines. The intent of this exercise was to create flowpaths and cooling models for different combinations of these key parameters, rerun the cycle analysis, and develop linearized variational coefficients for the dependent variables.

The first set of cycles was run with constant cooling flow and the component efficiencies previously described in discussing cycle evaluation. For this study, all axial compressors were used, because, in the flow sizes studied, they can achieve higher efficiencies than centrifugal stages. When the engine configuration and cycle study is narrowed axial/centrifugal configuration will be investigated in conjunction with duct losses and rotational speed studies. Parametric mechanical stress models were used to ensure that the airfoil shapes generated did not violate good design practice.

The results are shown in Figures 3 through 6. From the results a matrix of points, at which flowpaths were created were selected (Table 2). Efficiencies, cooling flows, and duct losses were calculated for each of these points. The numbers presented in Table 2 will next be used in the performance model to determine the optimum cycle point.

2.1 OPTIMIZATION OF TURBINE ROTOR INLET TEMPERATURE (TRIT) AND PRESSURE RATIO FOR BASELINE ARRANGEMENTS

The parametric study continues as cycle analyses, aerodynamic design, (compressor and turbine flowpath and airfoil count and meanline analyses) and cooling analyses are performed for the baseline arrangement at five different sets of firing temperatures (TRIT) and overall pressure ratios (PR), see Table 3.

The intent of the analyses is to establish the cycle efficiency sensitivity to the various parameters affected by TRIT and PR.

2.2 ASSUMPTIONS AND METHODOLOGY

Firstly, the preliminary cycle analysis was used as input to produce a preliminary design of the compressors and turbines and to develop turbine section cooling models. These data were used to develop revised cycle analyses and from these results the linearized variation in component efficiencies and cooling requirements was derived. Next, the PR and TRIT were varied over a matrix of values of from 5:1 to 26:1 and from 1850 to 2850° F respectively, with the LP and HP compressor pressure ratios optimized at each matrix point. The assumptions for the initial cycle analysis are the same as given in paragraph 1.1.

The data and assumptions used in deriving the coefficients for the parametric study are shown in Tables 3 and 4.

Note that the cooling flow amounts shown in Table 5 are calculated values of what is believed to be possible within a short time span. That is, no allowance is yet made to reduce cooling to very low levels through material and cooling development.

Table 2. Data From Parametric Cycle Studies for ATS

TRIT-PR- PARAMETER:	2350- 14:1	2450- 10:1	2450- 14:1	2450- 18:1	2550- 14:1
Turbine					
Gas Producer					
w corr	9.31	12.54	8.16	6.34	8.04
N	20050	18465	20687	23656	21300
PR	1.443	1.34	1.397	1.488	1.402
ETA	0.886	0.901	0.889	0.873	0.882
ETA cool	0.869	0.878	0.872	0.856	0.862
% Stator cool	0.28	1.84	1.53	1.3	1.76
% Rotor cool	3.13	3.21	3.39	3.15	4.09
% wcool	3.41	5.05	4.92	4.45	5.85
Inter-Turbine Duct					
% Del P/P	2.3	0	2.3	4	2.3
LP Compressor					
w corr	12.31	17.33	11.802	9.88	11.67
N	14865	16040	15342	14770	15800
PR	1.515	1.382	1.479	1.582	1.455
ETA	0.893	0.917	0.893	0.878	0.896
ETA cool	0.859	0.861	0.862	0.839	0.86
% Stator cool	0.28	0.28	0.28	0.28	0.28
% Rotor cool	5.14	5.81	5.57	5.5	5.69
% wcool	5.42	6.09	5.85	5.78	5.97
Inter-Turbine Duct					
% Del P/P	3	4	3	0	3
Power Turbine					
w corr	19.48	18.53	17.95	17.21	17.73
N	10440	10440	10440	10440	10400
PR (t-ds)	4.836	4.077	4.919	5.483	5.097
ETA (t-ds)	0.88	0.886	0.889	0.889	0.879
ETA (t-ds) cool	0.877	0.876	0.879	0.889	0.87
% Stator cool stage 1	0.28	0.28	0.28	0.28	0.28
% Rotor cool stage 1	1.19	4.2	4.04	1.56	5.23
% Stator cool stage 2	0	0	0	0	0
% Rotor cool stage 2	0.3	0.3	0.3	0.3	0.3
% Stator cool stage 3	0	0	0	0	0
% Rotor cool stage 3	0	0	0	0	0
% wcool	1.77	4.78	4.62	2.14	5.81
Total cool	10.6	15.92	15.39	12.37	17.63

Figure 3. ATS Cycle Optimization Study (RLP/RHP* = 0.727)
 Work Split - (LPC/HPC) Pressure Ratio
 For All Arrangements

Figure 4. ATS Cycle Optimization Study (RLP/RHP* - 0.875)
***Work Split - (LPC/HPC) Pressure Ratio**
For All Arrangements

Figure 5. ATS Cycle Optimization Study ($RLP/RHP^* = 0.923$)
*Work Split - (LPC/HPC) Pressure Ratio
for All Arrangements

Figure 6. ATS Cycle Optimization Study (Turbine Rotor Inlet Temperature [TRIT] = 2550 F)
For All Arrangements

Table 3. Range of Turbine Rotor Inlet Temperatures (TRIT) and Pressure Ratios Used to Parametrize (PR) Effects

TRIT, °F	PR
2350	14:1
2450	10:1
2450	14:1
2450	18:1
2550	14:1

Table 4. Compressor Parameters

TRIT, ° F	PR	Compressor Parameters, LP/HP				
		No. of Stages	Speed, RPM	PR	Polytropic Efficiency	Corrected Airflow, lbs/sec
2350	14:1	4/6	14865/20050	3.24/4.46	91.77/91.42	56.59/18.40
2450	10:1	3/5	16040/18645	2.74/3.76	90.78/91.33	57.37/21.99
2450	14:1	4/6	15342/20687	3.24/4.455	91.72/91.34	53.13/17.28
2450	18:1	5/7	14770/23656	3.67/5.056	91.90/91.62	50.93/14.66
2550	14:1	4/6	15342/21300	3.24/4.455	91.67/91.28	50.06/16.29

Table 5. Data From Parametric Cycle Studies for ATS

TRIT-PR- PARAMETER↓	2350-14:1	2450- 10:1	2450-14:1	2450-18:1	2550-14:1
Turbine					
Gas Producer					
w corr	9.31	12.54	8.16	6.34	8.04
Speed rpm	20050	18465	20687	23656	21300
PR	1.443	1.34	1.397	1.488	1.402
Efficiency	0.886	0.901	0.889	0.873	0.882
ETA cool**	0.869	0.878	0.872	0.856	0.862
% Stator cool*	0.28	1.84	1.53	1.3	1.76
% Rotor cool*	3.13	3.21	3.39	3.15	4.09
% wcool*	3.41	5.05	4.92	4.45	5.85
Inter-Turbine Duct					
% Del P/P	2.3	0	2.3	4	2.3
LP Compressor					
w corr	12.31	17.33	11.802	9.88	11.67
Speed rpm	14865	16040	15342	14770	15800
PR	1.515	1.382	1.479	1.582	1.455
Efficiency	0.893	0.917	0.893	0.878	0.896
ETA cool **	0.859	0.861	0.862	0.839	0.86
% Stator cool*	0.28	0.28	0.28	0.28	0.28
% Rotor cool*	5.14	5.81	5.57	5.5	5.69
% wcool*	5.42	6.09	5.85	5.78	5.97
Inter-Turbine Duct					
% Del P/P	3	4	3	0	3
Power Turbine					
w corr	19.48	18.53	17.95	17.21	17.73
Speed rpm	10440	10440	10440	10440	10400
PR (t-ds)***	4.836	4.077	4.919	5.483	5.097
Efficiency (t-ds)***	0.88	0.886	0.889	0.889	0.879
Efficiency (t-ds)	0.877	0.876	0.879	0.889	0.87
cool***	0.28	0.28	0.28	0.28	0.28
% Stator cool stage 1*	1.19	4.2	4.04	1.56	5.23
% Rotor cool stage 1*	0	0	0	0	0
% Stator cool stage 2*	0.3	0.3	0.3	0.3	0.3
% Rotor cool stage 2*	0	0	0	0	0
% Stator cool stage 3*	0	0	0	0	0
% Rotor cool stage 3*	1.77	4.78	4.62	2.14	5.81
% wcool*					
Total cool*	10.6	15.92	15.39	12.37	17.63

* Cooling air flow as percent of total compressor inlet flow

** ETA - cool = Cooling heat-exchange effectiveness

*** (t-ds) total to diffuser static

2.3 RESULTS

The results of the parametric study are shown in Figure 7. The gas turbine performance model used in this study is conservative in that it includes turbine cooling levels, component efficiencies and pressure losses that are achievable in the very near term. There are two reasons for this. Firstly, it is a logical step in the evolution of the product and the best method to obtain an accurate performance baseline. Secondly, it allows confirmation of assumptions during Solar's stepped-approach to reaching the ATS program efficiency goals. Thermal efficiency at or above 50 percent will be demonstrated once the improved turbine cooling, recuperator effectiveness and other technologies developed for the ATS are factored into the model. In sum, the trends relative to firing temperature pressure ratio shown in Figure 7 are representative, and do not imply an absolute value of thermal efficiency.

Figure 7 shows that the generally desirable trend for a pure cycle would be toward high TRIT, high PR operation. However, recuperator and combustor technologies development will dictate an upper limit for the PR. The search for cycle efficiency optima was limited to PR's below 20:1. A pressure ratio of 20:1 is considered to be a practical upper limit for recuperator materials that will be available by the year 2000. Figure 7 shows that there are two areas of TRIT and PR that require further study; the optimum at approximately 12:1 PR and 2250° F TRIT and the recuperator limited point at 20:1 PR and 2450° F TRIT.

3.0 EFFECT OF TOTAL COOLING LEVEL ON THERMAL EFFICIENCY

The intent of this study was to gain insight into the cooling level reductions that would be required as opposed to those required by today's technologies.

3.1 ASSUMPTIONS AND METHODOLOGY

The assumptions inherent to the cycle remain as stated in paragraph 1.1 and in Table 3 and Tables 4 and 5. The only added assumption for this portion of the analysis is that the hot section component cooling flows do not vary in relationship to each other. That is, if the total amount of compressor flow bled from the HPC discharge used to cool the hot section of the engine is varied by some percentage, the variation in the cooling air to any particular component varies by the same percentage.

3.2 RESULTS

Overall thermal efficiency versus overall PR for total cooling levels between 30 and 100 percent of the baseline level is plotted in Figures 7 through 10. Figure 7 is discussed in paragraph 2.3 and is the baseline. Figures 8 through 10 show the sensitivity of the cycles to changes in the total amount of HPC discharge air used to cool the hot section. It is evident from Figures 8 through 10 that there is a greater increase in thermal efficiency with decreased cooling in the higher compressor overall pressure ratios. In Figure 8 it is apparent that 50 percent thermal efficiency will be achieved at above 18:1 PR with TRIT above 2450° F at 80 percent of the baseline cooling level. In order to achieve 50 percent thermal efficiency at the cycle efficiency optimum previously observed in Figure 7 at lower pressure ratios (between 10:1 and 12:1 PR and 2250 to 2350° F TRIT), the total cooling level must be decreased to 60 percent of the baseline, Figure 9.

Figure 7. Solar GFATS Baseline 2-Spool Arrangement

Figure 8. Solar GFATS Baseline 2-Spool Arrangement, 80% of Baseline Cooling

Figure 9. Solar GFATS Baseline 2-Spool Arrangement, 60% of Baseline Cooling

Figure 10. Solar GFATS Baseline 2-Spool Arrangement, 30% of Baseline Cooling

A final iteration of the cycle study must be done in order to ensure that the aerodynamic, cooling design, and cycle analysis are completely converged. Once this is accomplished, the necessary calculations for input to the tradeoff analysis of the alternative arrangement described in paragraph 1.0 will be performed. These calculations will be similar in scope to that already reported upon for the baseline arrangement.

4.0 COMPONENT DESIGN WORK

4.1 RECUPERATOR

Materials temperature versus pressure envelope curves were generated for stainless steel type 347 and Haynes Alloy 230. Type 347 stainless is used in Solar's current line of recuperators.

Haynes 230 is an alloy that is under consideration for higher temperature applications. The data indicated that limitations exist at high temperatures and for high pressure ratio cycles. Oxidation and creep are the predominant life-limiting modes of the recuperator foils at elevated temperatures, usually associated with low-to-moderate PR. Short term failure modes will be the critical parameters in cycles with higher pressure ratio (above 18:1). Testing to address these issues is proposed as additional Task 8 effort.

Discussions were held with various vendors regarding manufacture of thin foil sheet for a dual metal recuperator. The dual metal recuperator would have certain advantages over a single material, as follows:

- The primary goal would be to reduce the cost of the recuperator by using high temperature alloy only where it is necessary to do so, and
- To use less expensive material elsewhere.

4.2 INTERCOOLER

A methodology was formulated for the intercooler design. The plan includes selection of an intercooler concept and its integration with engine design. The first step of this process entails establishing the size and cost of various intercooler designs along with their associated piping, gearbox, fan, ducting, support structure, etc.

An analytical model will be developed and validated for the selected intercooler concept. Working with the manufacturers, a cost model will be developed into the analytical model. At this point, a subroutine will be developed to integrate the intercooler with the engine to determine the optimum design for the intercooler when integrated with the engine.

Preliminary work has been performed on the feasibility of using a cooling tower as part of the intercooler system. As cooling towers are efficient heat transfer devices, one scenario is to use a small cooling tower as part of an indirect liquid-coupled system. This configuration would use a direct-water cooled heat-exchanger to directly cool the air from the first compressor. The cooling tower would then function as a second heat exchanger to reduce the temperature of the water coolant to close to ambient. The cooled water would then be recycled to the primary heat exchanger. Such a system can result in a higher effectiveness than would otherwise be possible.

Other secondary heat transfer devices will also be examined. These will include closed circuit (radiator) systems as well as raw water. The economics of ATS installation at a wide variety of sites will improve as more secondary cooling system options are available.

5.0 FUTURE INVESTIGATIONS

Early in the next quarter, a trade-off study will be conducted among the four ICR gas turbine arrangements examined during this quarter. This analysis will quantify the ability of each arrangement to meet ATS Program goals for thermal efficiency, low emissions, increased RAM and reduced cost of electrical power. A careful risk analysis of technological innovations will be included. At the close of this study, the selection of a preferred gas turbine cycle and physical arrangement, along with at least one alternative, will complete Task 3, "Selection of GFATS." This will allow Task 6 to proceed with a more detailed preliminary design of the core gas turbine as well as clearer definition of the recuperator, intercooler, control system and ATS package. The

insight gained into the effect of cooling air bleed during this quarter will also allow Solar's technical team to plan a high-yield, low-risk strategy for the Phase III development work.

During the execution of Task 6, the market study of Task 5 will bring additional input from the marketplace. This will include various customer preferences and prejudices as well as tangibles such as acquisition and installation costs and operating factors.

APPENDIX 1

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.
CFATS	Coal-Fired Advanced Turbine System.
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_t). Ratio of the work produced by a turbine to the work it extracts from the gas flow. When applied to a GP turbine, total-to-total efficiency is implied, this definition being based on total or absolute inlet and exit conditions. When applied to a power turbine, total-to-static efficiency is implied, thus accounting for static pressure recovery as a result of kinetic energy conversion in the exhaust diffuser.
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.
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.
PATTERN FACTOR	(Abbr. PF). A parameter defining the range of temperatures extant in the exit gas flow from a gas turbine combustor. $PF = \frac{T_{MAX\ EX} - T_{AVG\ EX}}{T_{AVG\ EX} - T_{AVG\ INLET}}$ <p>All temperatures are absolute.</p>
PF	See PATTERN FACTOR.
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.
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.
TRIT	Turbine Rotor Inlet Temperature. The average gas temperature entering the rotor annulus of the first turbine stage in a gas turbine. It is less than the average combustor exit temperature due to the mixing of spent cooling air flow from upstream sources, primarily the first stage nozzle vanes.

This cover stock is 30% post-consumer waste
and 30% pre-consumer waste, and is recyclable.

DOE/MC/30246-3844

Advanced Turbine Systems Program
Conceptual Design and Product Development

DOE

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

**Quarterly Report
November 1993 - January 1994**

K. W. Karstensen

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

**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
Solar Turbines, Incorporated
9250 Sky Park Court
San Diego, California 92123**

June 1994

DATE

FILMED

9/9/94

END