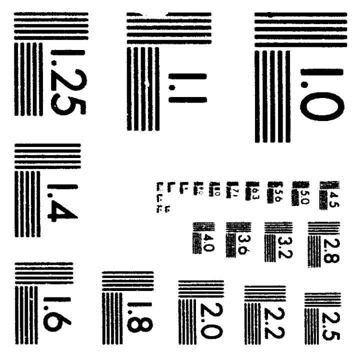
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Gas Fired Advanced Turbine System
Phase 1 - System Scoping and Feasibility Studies

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Authors:
R.T. LeCren
D.J. White

Contractor:
Solar Turbines Incorporated
P.O. Box 85376
San Diego, CA 92185-5376

Contract Number:
DE-AC21-86MC23166

Conference Title:
Joint Contractors Meeting: FE/EE Advanced Turbine Systems Conference, FE Fuel Cells and Coal-Fired Heat Engines Conference

Conference Location:
Morgantown, West Virginia

Conference Dates:
August 3-5, 1993

Conference Sponsor:
U.S. Department of Energy, Morgantown Energy Technology Center

1.3 Gas Fired Advanced Turbine System

Phase 1 - System Scoping and Feasibility Studies

CONTRACT INFORMATION

Contract Number	DE-AC22-86MC23166
Contractor	Solar Turbines Incorporated P.O. Box 85376 San Diego CA 92185-5376 (619) 544-5000
Contract Project Manager	Mr. Richard T. LeCren
Principal Investigators	Mr. David J. White
METC Project Manager	Mr. Paul Micheli

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The objective of the first phase of the Advanced Gas Turbine System (ATS) program was the concept definition of an advanced engine system that could meet the program's exacting efficiency and emission goals. The thermal efficiency goal for this advanced industrial engine was set at 50%, some 15 percentage points higher than current equipment levels. Exhaust emissions goals for oxides of nitrogen (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UH) were fixed at 8 parts per million by volume (ppmv), 20 ppmv, and 20 ppmv respectively, corrected to 15% oxygen (O_2) levels. Other goals also had to be addressed; these involved reducing the cost of power produced by 10% and improving the reliability, availability, and maintainability (RAM) over current levels. Although this advanced gas turbine was to be fueled with natural gas, it also had to embody features that allowed easy modification to burn coal or coal derived fuels.

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Marketplace Demands

Internal studies conducted with existing customers show that engine emissions and efficiency are rising rapidly in importance in the list of requirements demanded by the customer. It is believed that these two requirements will displace "first cost" from its second place on the list by the year 2000. These "key buying criteria" for industrial gas turbine customers are shown in Figure 1 for different time periods. Reliability, availability, and maintainability (RAM) are generally considered together to be the most important of all factors in buying gas turbines. This is not likely to change in the future.

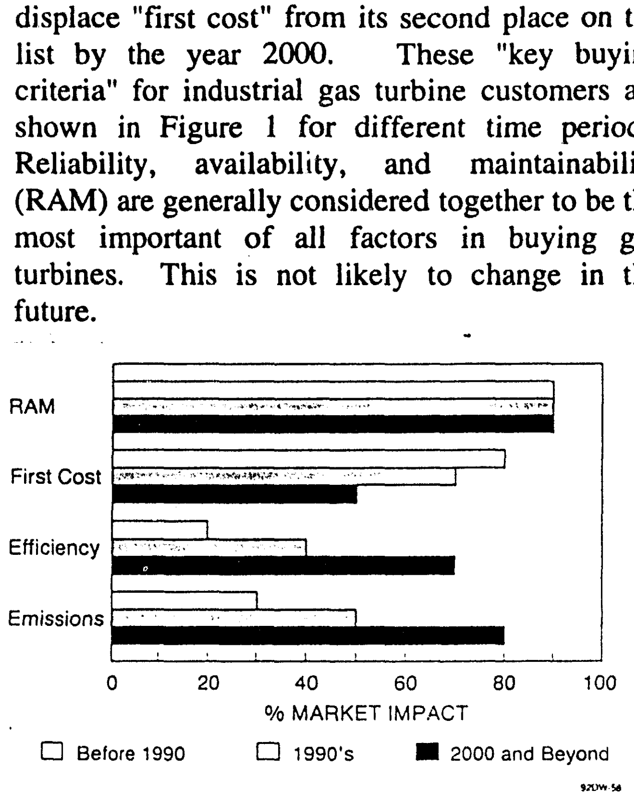

Figure 1. Key Buying Criteria

Advanced Technology Development

Solar intends to work with the U.S. Department of Energy (DOE) on all aspects of advanced technologies for energy conversion systems under 25,000 hp. These joint efforts will enable Solar and the U.S. industrial gas turbine community to maintain its leadership position and expand world market share, while creating new jobs in the process. As an example, Solar is working with the DOE on two ceramic programs: (1) to develop hot-end parts for existing gas turbines and (2) to develop the technologies to support the design of high temperature ceramic heat exchangers.

These two programs will provide invaluable technology support to the ATS program. The ceramic turbine program is considered critical to the success of ATS, and it is Solar's intent to use the technologies generated on the two programs and to forge synergistic relationships from them.

PROJECT DESCRIPTION

Information generated on previous Solar gas turbine development programs was used as a starting point for the first phase of the ATS program. For example, Solar has had considerable experience with combined-cycle and cogeneration systems that have demonstrated high efficiencies. The data available on these systems were used as a baseline to evaluate the various advanced engine options generated during the study. The simple-cycle gas turbine is the main type of machine offered in the market plac,e and is today the dominant design concept (Figure 2). Early in the system scoping, it became apparent that the traditional simple cycle machine would not be a practical approach to achieve the 50% thermal efficiency goal without some additional bottoming cycle.

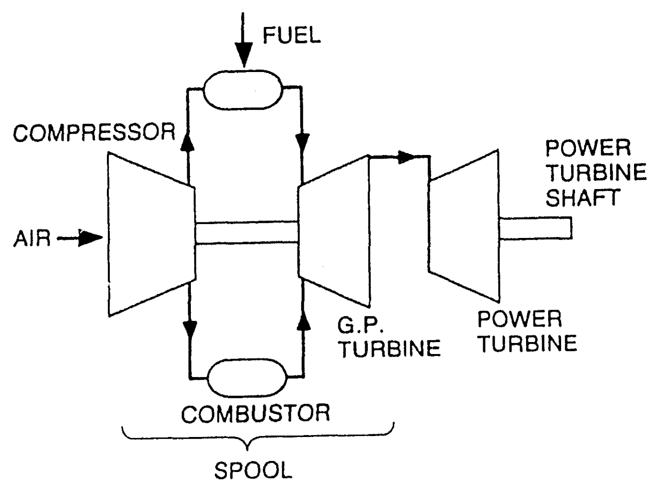

Figure 2. Simple-Cycle Gas Turbine System

Technical Challenges

Although the simple cycle gas turbine is today the dominant product sold by most industrial gas turbine manufacturers, the realities of tomorrow will force a change to other cycles. One of the reasons for this change is the difficulty in meeting the ATS efficiency goal with a simple cycle machine. From a practical point of view, it is impossible to achieve a 50% thermal efficiency with a simple cycle machine without resorting to some bottoming or topping cycles. Even accepting a lower efficiency would lead to significant problems. The high pressure ratios required for high simple cycle efficiencies (46%) are not practical in small size machines. Blade sizes on the last rows of an axial compressor providing pressure ratios on the order of 50:1 for a 16,000 hp machine will have to be extremely small. These blades would be expensive to produce and would have a limited efficiency life due to rapid erosion of the knife-like leading edges. This rapid loss in compressor efficiency would affect the overall thermal efficiency dramatically. Additionally, the small size of the blades in the first stage of the turbine section would make it difficult to employ some of the sophisticated cooling techniques needed to allow operation at temperatures on the order of 3000°F needed for the 46% efficiency.

Cycle Selection

As a consequence of the problems faced by the simple-cycle machine, Solar was forced to look at a number of more complex cycles. The theoretical Ericsson Cycle, as applied to the gas turbine, appeared to be one of the most attractive options. This cycle is shown as a temperature-entropy diagram in comparison with the Brayton Cycle in Figure 3. The area enclosed by the Ericsson Cycle is considerably greater than the corresponding area of the Brayton Cycle. This area is a measure of the work available and the greater the area, the more efficient the cycle.

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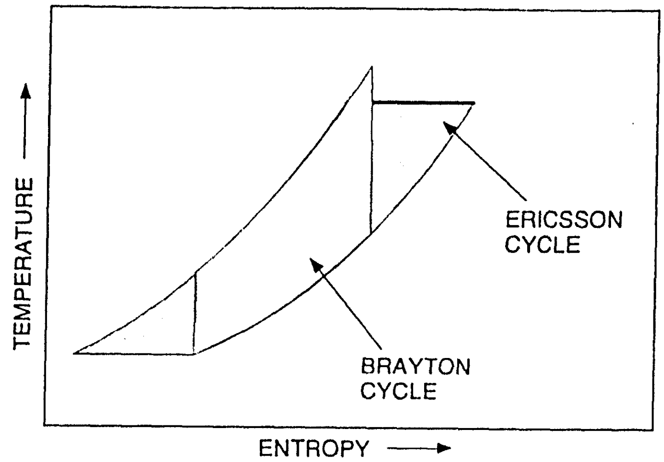

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RESULTS

The basic concept thus derived from the Ericsson cycle is an intercooled, recuperated, and reheated gas turbine. Theoretical performance analyses, however, showed that reheat at high turbine rotor inlet temperatures (TRIT) did not provide significant efficiency gains and that the 50 percent efficiency goal could be met without reheat. Based upon these findings, the engine concept adopted as a starting point for the gas-fired advanced turbine system is an intercooled, recuperated (ICR) gas turbine (Figure 4).

Turbine Cooling

It was found that, at inlet temperatures greater than 2450°F, the thermal efficiency could be maintained above 50%, provided that the turbine cooling flows could be reduced to 7% of the main air flow or lower. This dual and conflicting requirement of increased temperatures and reduced cooling will probably force the abandonment of tranditional air cooled turbine parts. Thus, the use of either ceramic materials or non-air cooling fluids has to be considered for the turbine nozzle guide vanes and turbine blades.

Turbine Section Materials

The use of ceramic components for the proposed engine system is generally preferred because of the potential growth to higher temperatures that is available with such materials. Figure 5 shows comparatively the performance of an ICR cycle using metallic components in one case and ceramics in the other. Similarly, Figure 6 depicts an ICR with reheat which, in one case, uses ceramic hot-end parts and, in the other, a metal-based turbine system. These two figures demonstrate the potentially significant improvements in efficiency that can be obtained by utilizing ceramic parts. In addition, by comparing the two figures, the differences between the reheated and non-reheated versions can be seen. These differences are not great at the

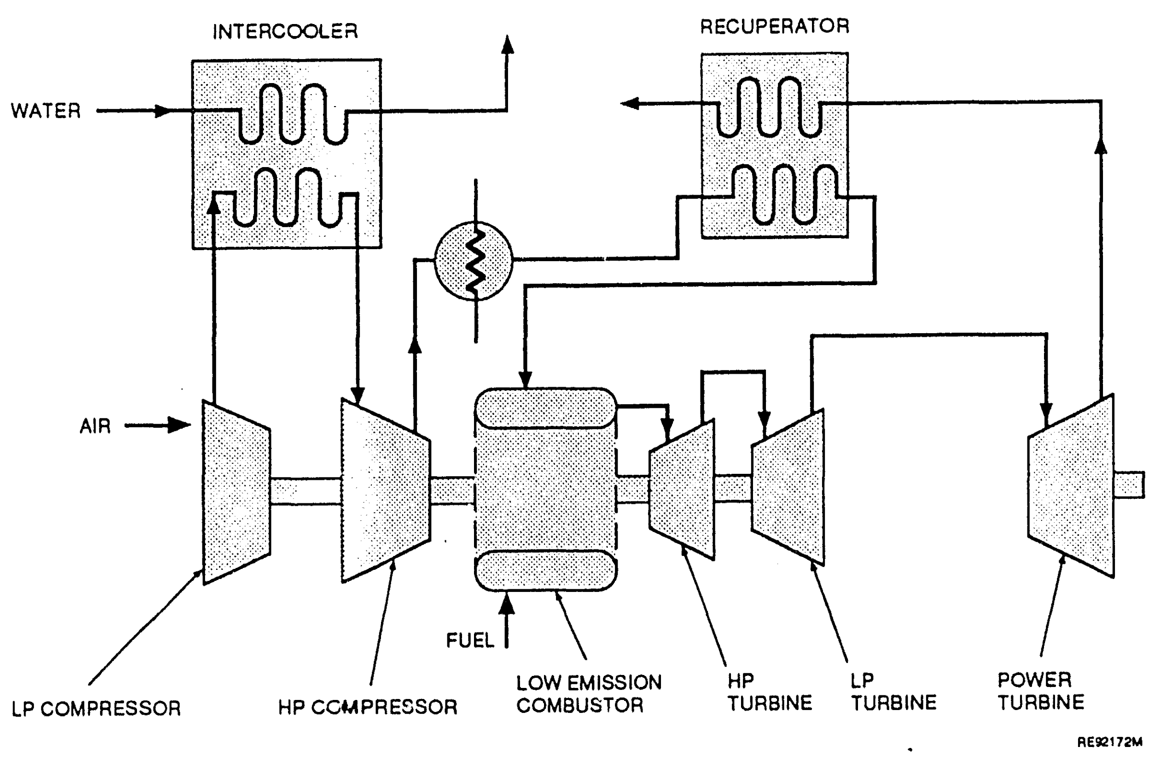
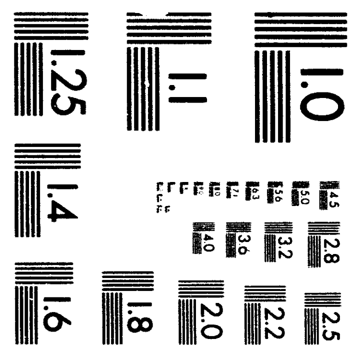


Figure 4. ICR Gas Turbine



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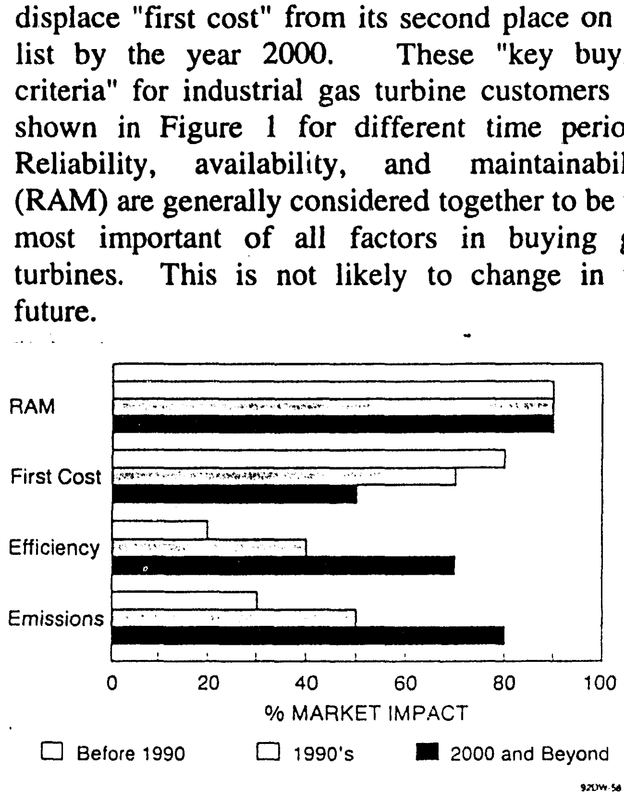

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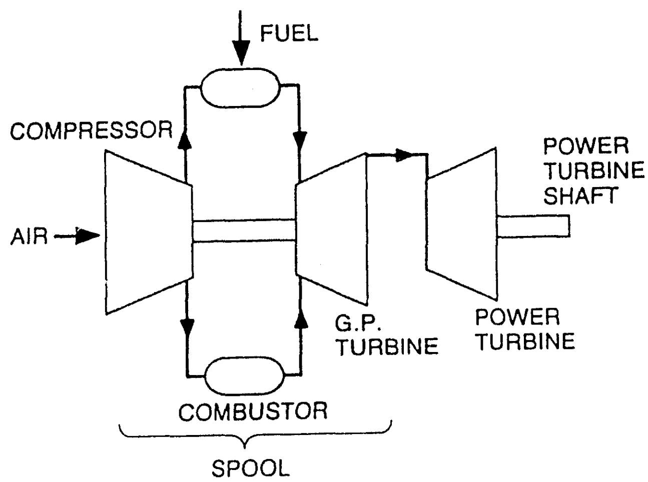

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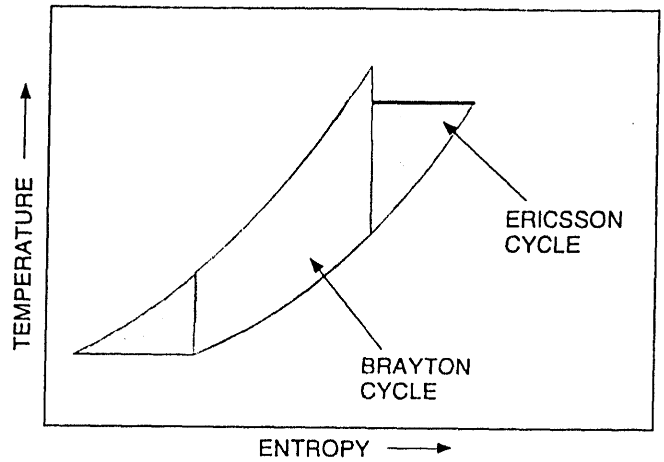

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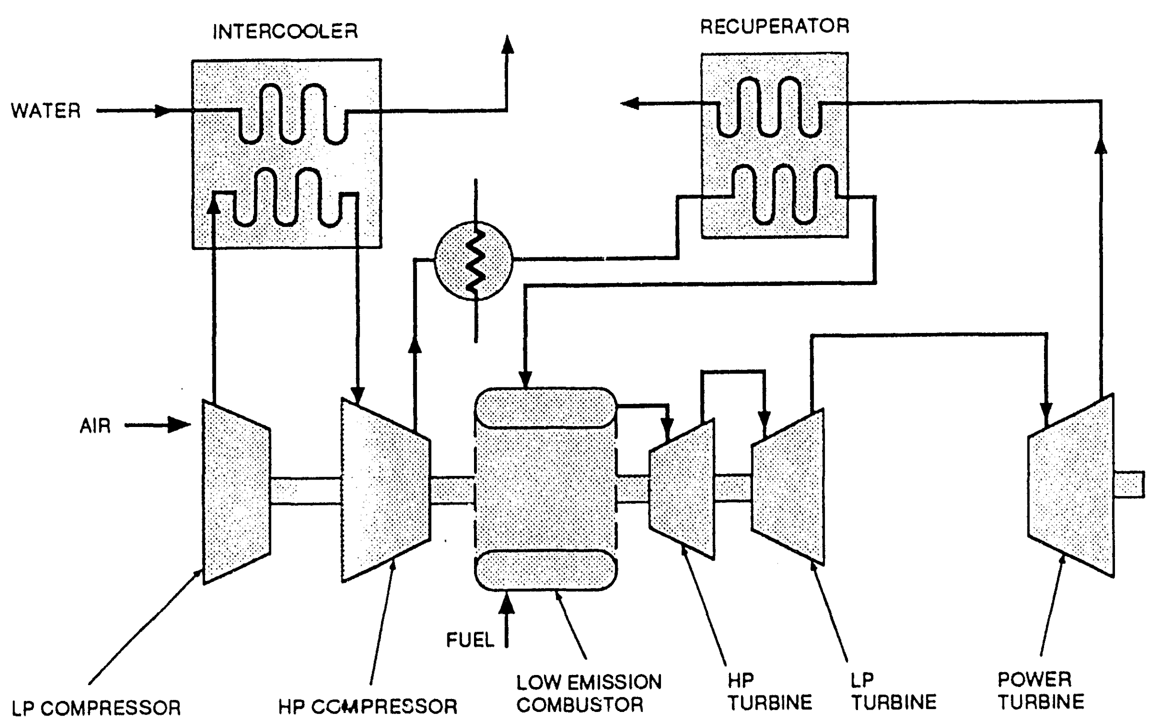

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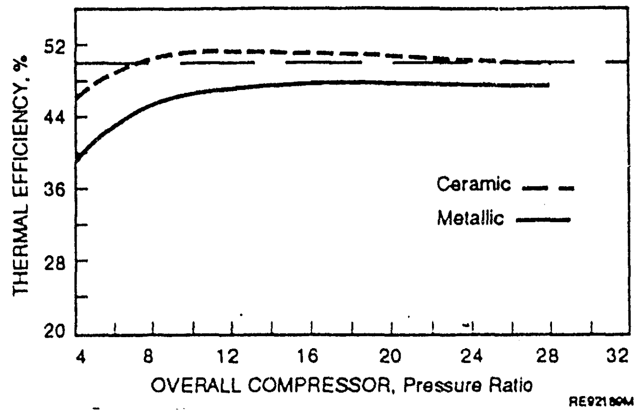

Figure 5. Intercooled Recuperated (ICR) Engine Performance

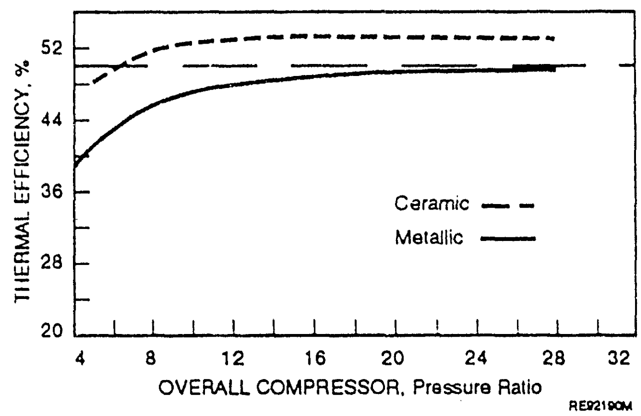

Figure 6. Solar Intercooled Recuperated and Reheat Cycle

lower pressure ratios where operation is more desirable. Generally, low pressure operation is preferred with natural gas-fired machines because of the energy penalties paid in compressing the fuel to pressures high enough to allow injection into the combustor. As the pressure ratio increases, the difference between the efficiencies increases due to a more rapid decrease in the efficiency of the ICR system.

The turbine and the hot-end parts in general will have to be fabricated from ceramic materials that have better performance than those materials available today. Fortunately, there are a number of programs world-wide that are developing these higher performance ceramic materials, and these should be available for the production ATS. Ceramic composites, perhaps silicon carbide fibers in a matrix of silicon carbide or silicon nitride may provide the primary structure for the turbine disks and related static parts. These composites will probably employ protective surface coatings such as alumina, silicon nitride, or boron nitride. The first-stage vanes and blades will probably be monolithic structures fabricated from advanced ceramics. These blades will utilize some form of air (or other fluid) cooling when operating at TRITs of 2450°F and above.

Other materials that will be considered include the intermetallics such as nickel aluminide and molybdenum disilicide. These materials may also be used as coatings on more conventional metal hot-end parts to minimize oxidation and thus allow operation at higher temperatures. Intermetallics when combined with thermal barrier coatings (TBC) may provide competition to the ceramic composites, and trade studies will have to be conducted to determine the better material set. Some of the newer formulations of yttria stabilized zirconia that utilize "bond coats" of platinum aluminide have demonstrated exceptional reliability at high temperatures. These bond coats are also compatible with the intermetallics, and thus this could lead to a new class of turbine materials.

Cycle Flexibility

If difficulties in meeting the efficiency goals are encountered, it is anticipated that reheat would be added to the basic ICR system proposed as a baseline. This adds complexity and cost; however, it also provides some benefits. It is possible with a reheat system, for example, to provide all of the load following from minimum to maximum load by modulating the reheat fuel flow. By using this approach, a flat but high-efficiency characteristic can be obtained. The response time of an engine using reheat is also much faster than other two-shaft gas turbine designs.

Solar will also consider the use of autothermal reforming of the natural gas fuel as an external add-on device. This type of approach would be adopted if difficulties in meeting the extremely low NO_x emissions required were encountered. When natural gas is reacted catalytically with steam in an autothermal reactor a high hydrogen content gaseous secondary fuel is produced. This secondary fuel has a lower heating value (LHV) that is greater (per unit weight) than the parent natural gas and can burn stably at much lower reaction temperatures. This ability to burn at very lean mixture ratios or low flame temperatures provides extremely low NO_x levels. In operation, the steam needed would be raised in the intercooler and boosted in temperature by a heat exchanger in the exhaust. Because thermal energy which normally goes to waste is being utilized in the autothermal reformer, very high system efficiencies can be obtained typically on the order of 60%.

An advanced engine system employing ICR, reheat, and autothermal reforming is shown schematically in Figure 7. The autothermal reformer, if used, would be integrated into the low emission combustor as shown in Figure 8. In practice, autothermal reforming could be used in those cogeneration applications where a periodic demand for steam is found. The steam raising, as described above, could be diverted for industrial use and, when not needed, passed to the auto-thermal reformer to maximize efficiency and minimize emissions. This would require a dual-fuel combustor. Such a system is entirely possible.

With the above options available to add on to the basic ICR concept, Solar is confident that all of the program goals will be met successfully.

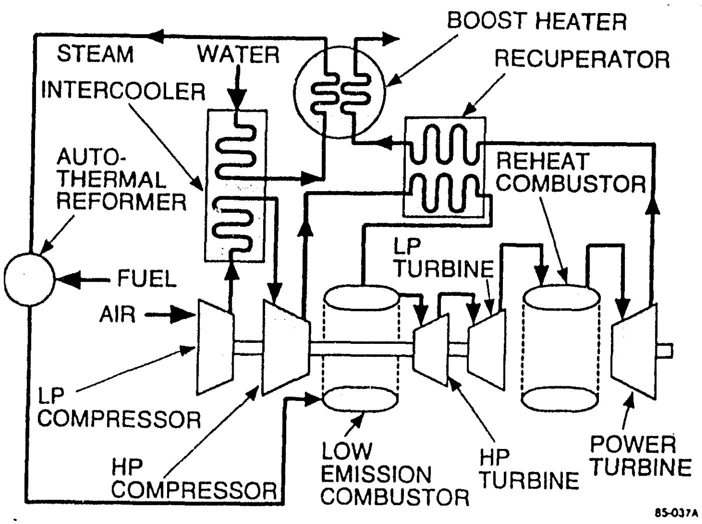

Figure 7. Advanced Turbine System (ATS)

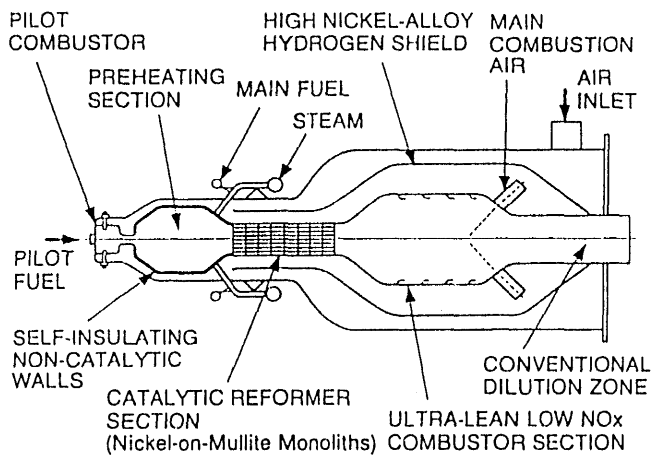

Figure 8. Integrated Autothermal Reformer and Combustor

FUTURE WORK

This paper summarizes the work performed by Solar in the first phase of a multi-phase program that culminates in the demonstration of two prototypical engine systems in 2002. Solar is certain that these gas turbine engines will meet the above-described goals and would be competitive in terms of price with all likely contemporary systems. Solar possesses the personnel, equipment, and the special interest to perform the aggressively paced developments required in the future phases of the ATS program. Solar welcomes the opportunity to participate in this challenging program, and is confident that the concept described herein will evolve into a highly successful product.

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