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2.2 Industrial Advanced Turbine Systems Program Overview

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Introduction

The U.S. Department of Energy (DOE), in partnership with industry, has set new performance standards for industrial gas turbines through the creation of the Industrial Advanced Turbine System Program. Their leadership will lead to the development of an optimized, energy efficient, and environmentally friendly gas turbine power systems in this size class (3-to-20 MW). The DOE has already created a positive effect by encouraging gas turbine system manufacturers to reassess their product and technology plans using the new higher standards as the benchmark.

Solar Turbines has been a leader in the industrial gas turbine business, and is delighted to have joined with the DOE in developing the goals and vision for this program. We welcome the opportunity to help the national goals of energy conservation and environmental enhancement. The results of this program should lead to the U.S. based gas turbine industry maintaining its international leadership and the creation of highly paid domestic jobs.

In a complementary paper at this conference, the details of our ATS Phase II program are discussed. This paper will describe Solar's approach to meeting the DOE objectives for the ATS Phase III program. It also covers the development of ceramic components under the Ceramic Stationary Gas Turbine (CSGT) program and the complementary High Performance Steam System (HPSS) Development Program.

Background

Government (DOE/Energy Information Agency) estimates of required new or additional power generation capacity in the U.S. are currently at 15 gigawatts annually after the year 2000. The products required to meet the increased demand for power will have to be highly efficient and environmentally benign. This expanding market will require products that have a life cycle of approximately 30 years. Additionally, and outside the scope of the aforementioned estimates, much of the old power generation equipment is reaching the end of its life and will need to be repowered or replaced with efficient and environmentally clean advanced systems.

The DOE has stated in its request for ATS Phase III proposals "... commercial implementation of the innovative technology is the principle goal of the Solicitation ..." The required program goals are:

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• **Efficiency** -- A 15 percent improvement compared to the best technology in its class, available in 1991.

• **Environment** -- Emissions will be lowered by 10 percent to achieve acceptance in severe non-attainment areas.

• **Fuel Flexibility** -- Natural gas-fired systems must be adaptable to future firing with biomass and coal derived fuels.

• **Cost of Power** -- Busbar energy costs should be 10 percent less than current state-of-the-art turbine systems, meeting the same environmental requirements.

• **Reliability, Availability, and Maintainability** -- Equivalent to current state-of-the-art turbine systems.

The DOE goals parallel those that Solar Turbines has set for its future products. The issue of product durability is a major buying criterion for users of industrial size gas turbines, and therefore Solar adds Durability to the above bulleted point of Reliability, Availability, and Maintainability. Solar’s nomenclature for this combined issue is RAMD.

**Maximizing Program Value**

The ATS program is designed to foster national goals of (1) global competitiveness of U.S. industry, (2) public health benefits, (3) reduction of dependence on imported oil, and (4) the expansion and retention of industrial employment through more affordable electric power. Other components of national value include increased product exports and reduced fuel imports. To achieve these goals the industrial partners must maximize the potential market volume, the market penetration by ATS technologies, and the technical performance gains. Market penetration has two components, (1) market acceptance and (2) time to market. Solar has taken each of these elements of program value into consideration when developing its plans for its ATS offerings.

**ATS Markets**

**Market Size**

The worldwide market for industrial gas turbine systems has doubled since 1985. Growth in market size is expected to begin around the year 2000 and continue at least through the year 2010. Acceptance of gas turbines into the growing power market is due to high availability, low initial cost, short delivery times, and the capability for dual-fuel operation and unattended (remote) operation.

**Market Characteristics**

Because the ATS will have system electric conversion efficiencies approaching 47 percent without heat recovery, the amount of thermal energy contained in the engine exhaust is relatively small compared to traditional cogeneration systems in the >70 percent range, depending upon site conditions and system operating requirements. Consequently, an ATS cogeneration system (e.g., unfired waste heat boiler) will have a higher electric-to-process steam production ratio (i.e., 5:1 versus 2:5) than traditional systems using less efficient gas turbines. Duct firing can be used to augment thermal energy output, when required.

Industrial prime mover applications, in general terms, have the following characteristics:
Prime movers are dispersed at or close to the site where their output is used.

The prime mover, and often the entire site, is either unattended or attended by personnel whose primary assignment is either elsewhere or unrelated to the prime mover.

The output of the prime mover is a critical element in the production of the site product but, unlike production machinery, must be transparent to the user.

The prime mover is frequently a significant cost element to the user.

These application characteristics will combine to produce a set of buying criteria similar to the set shown in Figure 1. These criteria vary somewhat from industry to industry, and trends can be observed over time. For example, emissions as a buying criteria, is growing rapidly in importance as regulatory activity increases. In non-attainment areas, emissions already heads the list, but still does not necessarily overpower reliability, availability, maintainability, and durability (RAMD) or cost. In the present economic milieu, first cost ranks very high but could yield to lifetime cost where fuel costs become high because of market pressure, or as a result of taxes on fuel usage.

**Market Segments**

The potential ATS applications within this large market are summarized as:

**Power Generation/Cogeneration**

**Power Generators:** The industrial ATS can be used as prime movers in electric power generation systems to meet the demands of electricity users. The owners and operators of ATS electric power plants can be investor-owned utilities, rural electric cooperatives, municipal utilities, and independent power producers. The continued growth of electricity demand at or above the nation’s Gross Domestic Product (GDP) through the remainder of this decade and beyond will create major opportunities for the ATS owning to its high efficiency, low capital cost, low prices for natural gas, short lead times for installation, and compliant environmental emissions.

**Cogenerators:** Typically, users of gas turbine cogeneration systems have had high heat-to-power ratios to justify supplying their process needs. With the development of the ATS systems, however, new markets with low-to-medium heat-to-power ratios will be able to justify cost-effective turbine cogeneration. Users in these markets will choose an industrial ATS system that meets their power and heat requirements.
**Dispersed Generation:** In the broadest context the ATS can be used in both traditional (i.e., baseload and cycling) and new (such as distributed generation) applications. Ease of siting and permitting, plus the improvement in the quality of power over that now available at great distances from the central station, or not available due to lack of capacity, are major attractions. Additionally, the ATS can be installed in areas where nuclear or older fossil fuel plants are scheduled for retirement.

**Traditional Industrial Markets**

**Oil and Natural Gas Production, Transmission, and Storage:** These industry sectors with a capacity between 5,000 hp and 30,000 hp, which depend extensively on compression and pumping equipment, represent clear opportunities for the ATS. The ATS, with its efficiency of nearly 47 percent, its low capital and maintenance cost, and its compliant emissions performance will be a very competitive option for the oil and natural gas industries. In addition, an American gas industry study [1] was conducted which concluded that gas turbines will continue to be the driver of choice for large compressors. Small gas turbines and electric motors will increasingly replace reciprocating engines on existing natural gas transmission pipelines.

**Industrial Prime Movers:** The ATS can be used for many industrial processes such as manufacturing power generation, mechanical shaft power for compressors and pumps in petrochemical and other energy intensive applications. Others uses include electric/thermal cogeneration to serve a portion of on-site electric and process steam demands in manufacturing plants which depend extensively on low-cost reliable electricity supplies.

**Transportation:** Propulsion applications in the commercial "fast ferry" and "fast freight" merchant marine industries appear to be the greatest opportunities for the ATS in marine applications because these applications emphasize fuel efficiency and power density. Gas turbine/electric motor drive combinations will power locomotives, in addition to the traditional diesel or diesel/electric drivers now in use. These applications are designed to use liquid fuels.

As currently envisioned, the ATS will have many attributes (e.g., low emissions, high availability) which will make it superior to advanced gas-fired power systems available in the marketplace after the year 2000. The projected cost and performance advantages clearly distinguishes it in contrast to its expected competitors.

**Market Transformation**

The industrial ATS program benefits will be maximized by (1) ensuring market acceptance and (2) getting the product to market early. These two issues combine to maximize the penetration of the ATS into the marketplace. The benefits provided by the ATS will accrue to both the customer and the public in general.

**Market Acceptance**

The customers in the markets discussed in the preceding sections share a common
characteristic - risk aversion. While the benefits of new technology are seductive, each of the market segment users wants to see proof of the new technologies before committing to purchase. Solar's approach to this issue is to involve customers in the evaluation of the technologies early in the program. Because of the large number of existing gas turbine systems supplied by Solar (over 9,400) in the industrial market segment alone, technologies can be introduced singularly and early into the field to gain acceptance. This process also ensures that early benefits are realized from each technology.

Customers look to Solar for upgrades to their equipment at the time of overhaul and understand the increase in value to their operations of dealing with a vertically integrated manufacturer. Prime mover, packaging and controls coordination has proven to suit the needs of the industrial gas turbine user.

Another facet of market acceptance is the company's reputation to stand by the customer. Solar's extensive field service network and service tools ensure that any problems encountered during the introduction of new technology are promptly resolved.

Acceptance of new technologies has been achieved by careful attention to the customer needs. Customer acceptance of industrial ATS technologies will hinge on proof of performance. Inclusion of the technologies into existing products as they are developed will help assuage the fears of customers who are not likely to accept unproven technologies. Therefore, Solar can incorporate the newly developed concepts and components into existing new products and to retrofit them into systems returned for overhaul. An example of this approach is the SoLoNOX™ dry, lean premixed, pollution prevention combustion system now available. Solar developed this technology and since its introduction in 1992, has sold over 250 of these systems. Two-thirds of the systems have been installed in new units for use worldwide, and the remaining one-third have been retrofit on units that have been returned for overhaul, upgrades, and uprates.

A similar process is planned for ceramic components which are being developed under the DOE Ceramic Stationery Gas Turbine (CSGT) program. These components are being designed for retrofit into a Solar Centaur® 50 gas turbine system. By investing in technology development, there have been significant accomplishments integrating the CSGT components into an existing gas turbine. Once proven in a field test engine, the components will be introduced to both new and retrofit markets in a low-risk approach.

**Early to Market**

Getting the product to market early, to help achieve the goals of the industrial ATS program, will be accomplished, only in part, by the retrofit process noted above. The bulk of the proof of concept comes in the investment in high-technology design tools and through the concept of rig testing. Solar uses the latest computer-based engineering design and analysis tools to reduce the uncertainties and time required for new developments. The proof of each design concept is confirmed through the extensive rig testing of each of the new component designs to assure performance and reduce the risks associated with placing unproven technologies into test engines. Of course, full field testing of all new concepts is completed before placing them in the marketplace.

This approach will allow the successful marketing of newly proven technologies, while satisfying the conservative, risk-averse nature
of the industrial gas turbine user. The success of the above-mentioned SoLoNOx systems was based upon standard industrial gas turbines that were retrofit with the development hardware and field-proven prior to market release.

Distributed Generation

In response to established national priorities, the DOE has provided partnering leadership through a number of cooperative programs with industry to significantly improve efficiencies and diversify fuel usage in industrial power generation equipment. The effect of these will be to satisfy our national energy requirements, while decreasing the amount and type of pollutants emitted to the atmosphere. The overall ATS program will provide an affordable solution for private industry, in cooperation with electric utilities, to restructure power generation technology toward the goal of dispersed electrical power production. To accomplish this goal, a new approach to supplying the capital equipment is required. Considerations for new power generation are becoming more involved. As a result, there are strong indications that today’s central plant, coupled to extensive transmission and distribution systems (Figure 2) will undergo a metamorphosis toward a new form of service called distributed generation.

Customer Choice

The advent of distributed generation brings with it a new challenge for the manufacturers and the end users of power generation equipment. Unlike the past practices, the customer or user of power now has a choice of technologies from which to choose (Table 1). The push of technological development and the associated market pull of users who select from the various alternatives will help determine which becomes the technology(ies) of choice. What is clear at this time is that the concept of distributed generation will offer the user highly reliable, quality power at an overall lower total energy cost.

Technical Performance Improvement

The market characteristics and customer buying criteria are essential inputs to the decision on product characteristics. Solar performed an extensive Quality Functional Deployment (QFD) analysis to quantify the customer needs in the industrial marketplace. A second set of key inputs came from the DOE program goals, especially early commercialization of ATS technologies. Commercialization demands market acceptance. Thus, Solar evaluated the types of technology that could be sold into the marketplace by the year 2000. Evaluation of numerous cycles against these criteria led Solar to select the optimized, recuperated gas turbine as the first step along the path of more complex cycle development (Figure 3). The development path will, of course, depend on the rate of customer
Table 1. Competing Systems for Electrical Generation [2]

<table>
<thead>
<tr>
<th>System</th>
<th>Availability, %</th>
<th>NO(_x) Emissions, ppmv</th>
<th>Installed Cost, $/kW</th>
<th>Thermal Efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Turbine Systems</td>
<td>98</td>
<td>5</td>
<td>650</td>
<td>42.8</td>
</tr>
<tr>
<td>Gas Turbine Combined Cycle</td>
<td>92</td>
<td>9</td>
<td>700</td>
<td>58</td>
</tr>
<tr>
<td>Conventional Gas Turbine</td>
<td>95</td>
<td>25</td>
<td>650</td>
<td>34.5</td>
</tr>
<tr>
<td>Molten Carbonate Fuel Cell</td>
<td>97</td>
<td>Trace*</td>
<td>3000</td>
<td>52.9</td>
</tr>
<tr>
<td>Reciprocating Gas Engine</td>
<td>91</td>
<td>42</td>
<td>600</td>
<td>39</td>
</tr>
</tbody>
</table>

* Does not include all emissions at other sources.

Industrial customers also require high thermal efficiency over a broad load range. The Solar ATS will achieve this with a variable area turbine nozzle (VATN). With this component the engine delivers almost flat heat rate over the 50-to-100 percent load range. A second advantage of the VATN is the flat or constant combustor firing temperature over the same load range. Because of this characteristic it is easier to maintain low emissions over the same load range.

Advanced Turbine Systems include more than the gas turbine driver. "Systems" includes the air inlets, exhaust silencers, gear boxes, generators, lube oil systems, fuel gas compressors, and controls. Each of these...
Table 2. Technology Development Categories

<table>
<thead>
<tr>
<th>Materials</th>
<th>Coatings</th>
<th>Efficiencies</th>
<th>Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Single Crystal Compressor &amp; Turbine</td>
<td>Thermal Barriers</td>
<td>Compressor &amp; Turbine</td>
<td>Lean Premixed</td>
</tr>
<tr>
<td>Blades, Nozzles</td>
<td></td>
<td>Components</td>
<td></td>
</tr>
<tr>
<td>Bi-metallic Recuperator</td>
<td>Rub Tolerant</td>
<td>Primary Surface</td>
<td>Ultra-Lean Premixed</td>
</tr>
<tr>
<td>Air Cells &amp; Turbine Disks</td>
<td></td>
<td>Recuperator</td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>Clearance Control</td>
<td>Cooling Improvements</td>
<td>Catalytic</td>
</tr>
</tbody>
</table>

items has an effect on system efficiency, cost, and availability. Some have an effect on air quality because of "fugitive" emissions. Calculations on a typical gas turbine system shows that eight percent of the engine output is not available at the busbar. Solar has addressed each item in the system reducing its parasitic power consumption and fugitive emissions. When these technologies are implemented, the optimized recuperated gas turbine system should have ~95 percent of shaft energy available at the busbar.

In conjunction with the industrial development of the energy conversion equipment, noted universities, led by Clemson, and including various campuses of the University of California working on combustion technologies, contribute to the technological research by analyses and experimental testing of the theories and/or future concepts developed under DOE contract to the industrial partners. A listing of the partners is shown in Figure 4.

Figure 4. Industry/University Consortium

Ceramic Stationary Gas Turbine Program

Introduction

The Industrial ATS program has been designed to have associated technology development programs used as feeder programs into the main program. The Ceramic Stationary
Gas Turbine (CSGT) program is one such feeder program. CSGT is predominantly a materials development program that advances the enabling technologies that will feed into and help develop the ATS turbine system design as a forward-fit development, and will enable retrofit to existing systems when the materials are proven.

Objective

The overall objective of the DOE Ceramic Stationary Gas Turbine (CSGT) Development Program is to improve the performance of existing stationary gas turbines through the selective replacement of metallic hot section parts with uncooled ceramic components. The successful demonstration of ceramic gas turbine technology, and the systematic incorporation of ceramics in existing and future gas turbines will enable more efficient engine operation, resulting in significant fuel savings, increased output power, and reduced emissions.

The objective of the CSGT program is to demonstrate and ultimately commercialize ceramic gas turbine technology with the intent of providing national energy savings and emissions reductions. The economic and technical potential of the ceramic gas turbine technology has been analyzed and described in the Phase I Final Report for the CSGT program. The application of ceramic components benefits gas turbine performance because it enables a higher component temperature in a simpler and therefore, less costly, design and/or it reduces the need for part cooling and the use of protective coatings. When considering the cost associated with utilizing ceramic blades and nozzles, one can assume that ceramics will be (1) more expensive than uncooled parts of conventional superalloys, (2) are of comparable cost as cooled conventional superalloy parts, and (3) can be significantly less expensive than parts fabricated of cooled and coated advanced superalloys.

Estimates of potential national energy savings and emissions reductions as a result of implementing ceramic gas turbine technologies in industrial engines (0.5-25 MW output) have been made as part of the Phase I work. Potential annual national energy savings have been estimated to range from 0.076-0.28 quads (1 quad = 10^{15} Btu) or between 14 and 56 million barrels of oil, by 2010. The lower end of this range assumes a modest penetration of the projected engine fleet with first generation retrofits. The higher end of the range assumes that the entire installed fleet will consist of second generation ceramic engines.

Phase II work to date includes the completion of the first generation ceramic component designs and the design of the interfacing metallic support structures, fabrication of subscale components, and full scale prototypes. The set-up and modification of test rig facilities, testing of specimens, and subscale components has also been completed. The generation of a long term data base and the development of supporting technologies, such as NDE have been generated. Testing of full scale prototype components in rigs and in the program engine was started at the end of the reporting period. The full-scale test of the first ceramic hot-section components in an industrial gas turbine has been successful.

High Performance Steam Developments

Possibly the world’s highest temperature steam power plant has successfully completed the development test phase. Results represent a breakthrough in steam technology. Based upon a successful 500 hour test cell demonstration of a 1500°F (815°C), 1500 psig
(10,342 kPa) generator in 1991, the complete full-scale system has been designed, fabricated, and completed development testing. Included in the system is an industrial size steam generator fired by natural gas, a triple function steam valve, and a 4 MW topping steam turbine. All of the three major components and the piping are innovative and represent a major advancement in design, materials applications, process development, and manufacturing technology.

To cost effectively develop and introduce advanced steam systems to industry, a natural gas-fired industrial-sized combined cycle was selected as the optimum configuration for development by the DOE. A gas turbine used extensively for cogeneration was used for calculating steam generator sizes for a combined-cycle system with a back pressure steam turbine arrangement (Figure 5). A supplementary exhaust firing system providing a temperature of 2500°F (1371°C) was selected on the basis of maximum economic performance in cogeneration while maintaining ultra-low emissions capabilities. At an exhaust flow of 38 pounds (17.2 kg) per second the output steam flow is 57,000 pounds (25,855 kg) per hour at 1500°F (815°C) and 1500 psig (10,342 kPa). In a combined-cycle configuration with a back pressure steam turbine the system is designed to produce 9 MW of electrical power, and 990°F (532°C) high quality process steam. The overall process efficiency, steam and electricity, is above 90 percent fuel utilization efficiency and about twice the amount of electric power is produced per pound (kg) of steam to the process.

The steam generator employs a once-through water steam flow path with a horizontal gas flow path. The majority of the heat transfer area is in carbon steel fins brazed to high nickel stainless steel tubes. In the final superheater section specially developed

![Figure 5. HPSS for Cogeneration](image)

Inconel 617 tubes are used above metal temperatures of 1300°F (704°C). All three major components, steam generator, piping, and valve were operated at full steam flow and at a temperature of 1500°F (815°C) and 1500 psig (10,342 kPa) prior to operating the steam turbine. Outlet temperature of the 26 circuits was adjusted to obtain outlet temperatures of within +95°F about an average measured mixed temperature of 1508°F (820°C). Emissions at natural gas firing rate of 110 million Btu (116 million kJ) per hour were equivalent to 9 ppm NO, and 7 ppm CO at 15 percent oxygen (test was at 3.2 percent oxygen).

The steam turbine design is a synthesis of gas turbine design concepts and steam turbine materials. The diameter of the turbine is small to permit high temperature and pressure operation. With a blade pitch diameter of 11.5 inches (29.2 cm), the operating speed is 30,000 rpm using a single-stage supersonic impulse design. It is a full admission with an overhung single rotor. This provides for centerline axial flow steam admission with complete symmetry. Only the static superalloy investment cast inner case is exposed to 1500°F (815°C) steam. Over 2.5 billion forcing pulses at full power were applied to each blade at their undamped natural frequency during the test. During the 100 hour
technology proof tests, the steam generator, triple control valve, and steam turbine and interconnecting piping system performed extremely close to analytical estimates. The expansion efficiency from 1500°F (815°C) and 1500 psig (10,342 kPa) to 165 psia and 990°F (532°C) was 68 percent for the single-stage turbine. The rotor and case steam cooling system kept cooling steam on the nozzle side of the rotor only 70°F (21°C) above the exhaust of 990°F (532°C).

Successful advancement of steam temperature conditions in the HPSS program can further the basic goals of the ATS programs. Those ATS systems with high gas turbine exhaust temperatures can consider HPSS topping steam turbines to obtain higher efficiency and more power. Lower exhaust temperature ATS systems will obtain significant advantages through use of supplementary firing and using HPS concepts for cogeneration applications.

Summary

Under the continuing ATS Conceptual Design and Product Development (Phase II), market studies were conducted to help establish the product configuration(s) acceptable for use in the newly emerging dispersed/distributed electric power generation market. In parallel, the future technology needs of the established industrial markets in mechanical drive gas turbines were addressed. These studies revealed a mix of acceptable future power generation technologies. The initial responses have led to the design of a gas-fired, recuperated, industrial size gas turbine. Solar has recently been awarded Phase III, for development and demonstration of this design.

The CSGT Phase II program, which commenced in April 1994 continues. A full-scale test of the first ceramic hot-section components in an industrial gas turbine has been successful. Long-term testing of ceramic components for performance and life assessment is continuing.

The HPSS Phase III development program takes a substantial step toward increasing industrial and electric utility prime mover efficiency. A 100 hour development test to prove the advanced, 1500°F, 1500 psig system full-scale hardware has been successfully completed.

The DOE ATS program will advance the development of environmentally clean, highly efficient gas turbine and related products for new markets, and for retrofit and repowering markets where there will be a need for large blocks of power. However, a market transformation will take place, where the customer will be offered a choice of energy conversion technologies to meet heat and power generation needs into the next century.

References