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THE U.S. DEPARTMENT OF ENERGY'S ADVANCED TURBINE SYSTEMS PROGRAM

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ABSTRACT

Advanced Turbine Systems (ATS) are poised to capture the majority of new electric power generation capacity well into the next century. U.S. Department of Energy (DOE) programs supporting the development of ATS technology will enable gas turbine manufacturers to provide ATS systems to the commercial marketplace at the turn of the next century.

A progress report on the ATS Program will be presented in this paper. The technical challenges, advanced critical technology requirements, and system configurations meeting the goals of the program will be discussed. Progress has been made in the areas of materials, heat transfer, aerodynamics, and combustion. Applied research conducted by universities, industry, and Government has resulted in advanced designs and power cycle configurations to develop an ATS which operates on natural gas, coal, and biomass fuels. Details on the ATS Program research, development, and technology validation and readiness activities will be presented. The future direction of the program and relationship to other Government programs will be discussed in this paper.

INTRODUCTION

More than 15-gigawatts (GW)-per-year of gas turbine equipment is manufactured today in the United States (U.S.). This translates to a product value of more than $3.5 billion, when the balance of plant equipment is included.

Electricity demand from both natural gas and coal is projected to increase significantly through the year 2015 to meet increased demand for electricity in the U.S. and offset the decline in generation from nuclear power (Annual Energy Outlook, 1997). With the low cost of natural gas and relatively low capital requirements for gas-fired capacity compared to coal-fired capacity, natural gas nearly triples its share of electricity generation between the years 1995 to 2015. Increased demands for power, coupled with low fuel costs and the relatively low capital cost of gas turbines will enable gas turbines to capture a large portion of the growing electric power market. The Energy Information Agency estimates that gas turbines will satisfy up to 81 percent of new electric power demands in the U.S.

Since the inception of the ATS Program, further insights have been gained into the risks of developing ATS. The growing need for lower nitrogen oxide (NO_x) emissions, high power densities in individual machines, and high efficiencies to keep natural gas consumption and costs low has driven rapid introduction of new technology. Two critical issues have emerged recently from problems with advanced turbine designs: (1) The need to better evaluate risk and (2) the need for the industry to focus on life-cycle costs (Makanski, 1996).

These insights have emphasized the critical need for Government participation in the ATS Program. Financial support for the ATS Program is provided by DOE and the individual ATS Program participants. The level of cost sharing required from the participants increases as technology risk decreases. During the final phases of the ATS Program, participants will provide more than 50 percent of the financial support needed to sustain the program.

The ATS Program is developing two classes of gas turbines. Simple cycle industrial gas turbines, less than 20 megawatts (MW) in capacity, are being developed for distributed generation, industrial, and cogeneration markets. Gas turbines, greater than 20 MW, used in combined-cycle systems, are being developed for large baseload central station electric power generation markets. Turbines smaller than nominally 3 MW are not covered by the ATS Program.

Projects in the ATS Program are organized under two major activities: (1) *Major systems development* and (2) *technology base development*. The ATS Program participants under the *major systems development* activity are turbine manufacturers actively engaged in developing an ATS. Currently, there are four turbine manufacturers working on detailed engine designs and hardware under the technology readiness and validation testing, or Phase III of the ATS Program. The *technology base research* activity consists of projects to support the major systems development and evaluate future advancements for gas turbine systems. Academic research and applied research not currently targeted for incorporation into ATS demonstrations is supported under this activity.

The objectives of the ATS Program are to develop low-cost, highly efficient gas turbine systems which possess superior environmental performance. The specific program objectives are:

- **Efficiency** – greater than 60 percent (lower heating value (LHV)) on natural gas for large-scale utility turbine systems or 15 percent improvement in efficiency for smaller industrial turbine systems.
- **Environmental Superiority** -- NO_x emissions less than 9-parts-per-million (ppm) and carbon monoxide and unburned hydrocarbon emissions, less than 20 ppm, without post-combustion cleanup.
- **Fuel Flexibility** – initially designed for natural gas fuel with adaptability for coal-derived and biomass fuels.
- **Cost of Power** – busbar energy costs of 10 percent less than state-of-the-art (1992 vintage) turbine systems meeting the same environmental requirements.
- **Reliability, Availability, and Maintainability** – equivalent to, or better than, current state-of-the-art systems.

ATS MARKET

A recent market study sponsored by Westinghouse Electric Corporation (U.S. DOE's, Office of Fossil Energy, Office of Energy Efficiency and Renewable Energy, 1995) projects a significant market for ATS. Total world electric power generation demand from the years2000 to 2014 is estimated to exceed 1,690 GW.

Natural gas, the market-entry fuel for ATS, is projected to supply 473 GW of the increasing world market demand for power during this period. The potential market for utility-scale (combined cycle) and large simple cycle ATS is very large and exceeds 300 GW. Markets for small, industrial-scale turbines is projected to be up to 127 GW.

Solid fuel-based gasification power systems will incorporate ATS technology. ATS penetration into the Integrated Gasification Combined Cycle (IGCC), Pressurized Fluidized-Bed Combustion and Indirect-Fired Cycles markets is expected to increase in the post 2005 to 2010 timeframe, as solid-fuel-based power system commercialization accelerates.

RELATED ATS DEVELOPMENTS

The highest thermodynamic efficiencies of commercially operating gas turbine combined-cycle powerplants have achieved levels of 55 percent, with good prospects of 60 percent within the next 4 years. Gas turbine manufacturers are developing advanced systems and have made significant progress since the inception of the ATS Program. Manufacturers not participating in the program have chosen to take different approaches to developing advanced gas turbine systems (Susta and Ludy, 1997). Siemens has developed the V84.3A series with a simple cycle efficiency in excess of 38 percent and combined-cycle powerplant capability above 58 percent efficiency (Oeynhausen, et al., 1996). Siemens has incorporated single crystal (SX) blades and anti-corrosion coating which provide high resistance to oxidation. Siemens anticipates operation with inlet temperatures in excess of 1500 °C, with overall combined-cycle efficiency of 60 percent within the next few years. This will be accomplished with progress made in steam turbine technology (Stambler, 1996).

Mitsubishi Heavy Industries has developed the 501G series and is currently verifying the long-term durability of the system with the 330 MW combined-cycle powerplant at its Takasago works in Japan (Modern Power Systems, 1997). New technology innovations, such as a steam-cooled, dry, low-NO_x combustor have been successfully incorporated into the G-series, after stringent operational tests.

Advances have been made with industrial-scale turbines. Allied Signal recently released a new series of compact, dry, low-NO_x designs from 3.3 to 10 MW, which will compete with less efficient machines in the same size (DeBasis, 1997).

PROGRAM STATUS

Phase II – Concept Development

Currently, four major turbine manufacturers are participating in Phase III of the ATS Program, Technology Readiness and Validation Testing. Allison Engine Company and Solar Turbines are developing industrial-scale ATS. General Electric Company (GE) and Westinghouse are developing utility-scale ATS.

Each of the major ATS developers has completed a conceptual design under Phase II of the program, Concept Development. While these designs differ in specifics, there are many common features. Generally, turbine manufacturers will increase turbine inlet temperatures; develop lean, premixed or catalytically enhanced combustors; reduce cooling air use through improved cooling schemes, improved materials, or improved seals; improve aerodynamic designs; scale-up materials manufacturing methods; and develop improved thermal barrier coatings (TBC's).

Cycle Designs. Industrial ATS developers are pursuing somewhat different approaches to achieve the cost and performance objectives of the program.

Allison Engine Company is pursuing an approach based upon their extensive aircraft gas turbine experience. Increased efficiency for their simple cycle engine is achieved by raising the turbine inlet temperature (400 °F) and pressure ratio 30:1). Allison's approach is to develop a "core" ATS engine that will serve multiple applications (5 to 15 MW), with overall cycle efficiency of nearly 41 percent (Mukavetz, 1995).

Solar Turbines is pursuing an alternate approach which utilizes a recuperated cycle. The Solar concept takes advantage of their proprietary primary surface recuperator, with an effectiveness exceeding 90 percent and with demonstrated long-term performance and reliability. Solar's cycle provides (43 percent) efficiency at a more modest turbine inlet temperature (2000 °F) and pressure ratio (9:1) (Gates, 1995). Figure 1 is a generic schematic of the cycle designs selected by the industrial ATS developers.

Utility-scale ATS developers, GE (Chance, 1995) and Westinghouse Electric Corporation (Diakunchak, 1995), are both developing large gas turbine combined-cycle systems greater than 400 MW. Each of these systems incorporates a unique closed-loop cooling concept that improves system efficiency and maintains superior environmental emissions. Closed-loop steam cooling utilizes the superior heat transfer characteristics of steam, as compared to air, and also enables better integration between the gas turbine and steam turbine cycles. Figure 2 depicts a generic schematic of the closed-loop cooling configuration selected by the utility-scale ATS developers.

GE's ATS, the Steam and Gas Turbine 107H, is a 400-MW combined-cycle system, with an overall efficiency in excess of 60 percent LHV. The high system efficiency is achieved by increasing turbine inlet temperature to 2,600 °F and incorporating many advances from GE's aircraft gas turbine business. An 18-stage

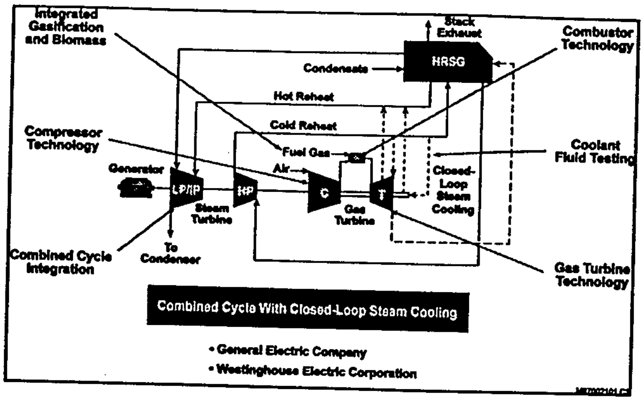

FIGURE 1. INDUSTRIAL ATS

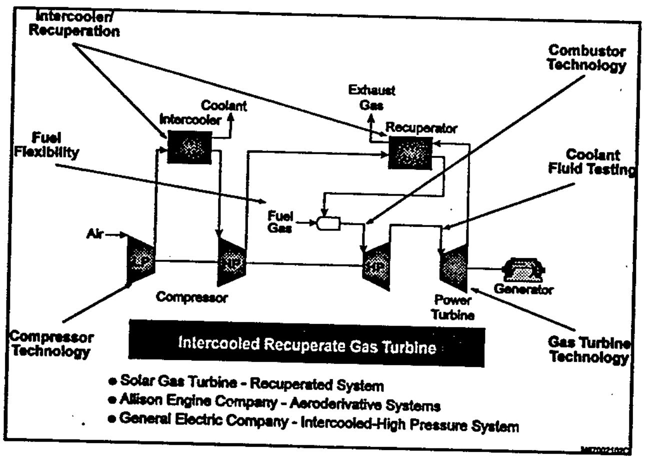

FIGURE 2. UTILITY

compressor, scaled up from GE's CF6-80C2 aircraft engine, is capable of delivering 1,230 lb/s of air at a 23:1 pressure ratio.

Similarly, Westinghouse is developing a combined-cycle ATS system capable of producing 420 MW, with an overall system efficiency in excess of 60 percent LHV. The Westinghouse ATS operates with a turbine inlet temperature of 2,750 °F. A high-efficiency, 20-stage compressor, capable of delivering 1,200 lb/s of air at a 29:1 pressure ratio enables Westinghouse to achieve its ATS target.

Table 1 shows the performance for the four major developers' ATS configurations.

Efficiency Improvements. To improve cycle efficiency, all ATS developers will increase turbine inlet temperature. Emphasis on increased efficiency and higher firing temperatures requires the use of improved materials with superior creep and thermal resistance characteristics. First-stage airfoils will be SX with directionally solidified or conventionally cast airfoils in subsequent stages. Additional thermal protection will be provided by TBC's applied to blades, vanes, combustor liners, and other components exposed to high temperatures.

Although a higher risk technology, ceramic materials offer the advantage of increased turbine inlet temperature without the need for blade and vane cooling air, thus improving system efficiency. The low expansion characteristics of ceramic seals and spacers also ensure tighter dimensional tolerances that lower the amount of performance-robbing gas leakage.

For industrial-sized turbines, these advantages of ceramics show a potential to improve efficiency as much as 2 percentage points. All developers have a ceramic option for their ATS. Both monolithic ceramics and continuous fiber ceramic composites (CFCC) are under consideration.

DOE's Ceramic Stationary Gas Turbine (CSGT) Program and CFCC Program directly support the ceramic activities of the ATS. Both Solar Turbines and Allison are doing programs that will install and test ceramic materials in currently available engine models. Under the CGST, Solar Turbines is testing a Centaur 50S engine that incorporates monolithic ceramic first-stage blades and a ceramic composite combustion liner. ARCO Western Energy in Bakersfield, California, operates the turbine in a cogeneration mode. The CSGT meets ARCO's contractural requirements for supplying power to the local utility grid. Simultaneously, exhaust heat from the turbine produces steam for enhanced oil recovery. Moreover, without water injection, the CSGT at ARCO consistently achieves allowable emissions. Having achieved 1000 hours of commercial operation, the CSGT represents the world's first successful demonstration of ceramics on an industrial gas turbine.

Both utility ATS systems incorporate closed-loop cooling of the first and second turbine stages, which provides significant improvements in efficiency. Closed-loop cooling increases turbine inlet temperature without increasing combustion temperatures. This approach permits high turbine inlet temperatures, without increasing environmental pollutants, such as NO_x. Current state-of-the-art gas turbines use compressor discharge air to cool the first-stage nozzle by injecting a stream air through the nozzle to provide film cooling. This maintains turbine blade materials at acceptable temperatures but results in an overall decrease in performance. With closed-loop cooling, media, either steam or air, is not injected into the gas stream, thus allowing more heat/energy to be transferred to subsequent stages in the gas turbine. This allows more work to be extracted from the gas flow and improve cycle performance. GE has designed their ATS for closed-loop steam cooling of the first two stages of gas turbine inlet vanes and blades, while the Westinghouse design requires steam cooling for the first two turbine inlet vanes (McQuiggan, et al., 1996; Schonewald and Fric, 1996). Studies by both GE and Westinghouse indicate that closed-loop cooling offers system efficiency improvements of up to 2 percentage points.

Methods to reduce leakages and improve seals are being developed to withstand the increased pressures and temperature of ATS. Seal designs and configurations are under evaluation to reduce leakage in the turbine nozzle, turbine shroud, and between turbine stages. Active tip clearance control is also being used to reduce leakage of working fluid. Advanced aerodynamics, design, and fuel preheating are other options manufacturers are using to further increase system efficiency.

ASEA Brown Boveri Combustion Engineering (ABB) continues work on their Conceptual Design and Product Development Phase of the ATS Program to upgrade their GT24 reheat gas turbine combined cycle to ATS operating conditions (Mayer, 1996). ABB is addressing technical barrier issues for high-temperature, high-efficiency gas

TABLE 1

	Industrial ATS Systems		Utility ATS Systems	
	Allison	Solar	General Electric	Westinghouse
Cycle Configuration	Simple	Recuperated	Combined Closed-Loop Cooling	Combined Closed-Loop Cooling
System Size (MW)	5-15	5, 15	400	420
Turbine Inlet Temperature (°F)	2400-2600	22,000	2600	2750
Pressure Ratio	30:1	9:1	23:1	29:1
NO_x(ppmv)	9	9	9	9
Efficiency (% LHV)	41	43	> 60	> 60

turbines. Some of the main barrier issues are reliability of TBC systems under high temperature and cyclic operations, highly efficient air-cooled systems, use of steam as a coolant medium, and aerodynamic cooling interaction in high-efficiency turbine designs. ABB has commissioned a turbine test rig at the Massachusetts Institute of Technology to measure aero-cooling interaction under full operating conditions, which is unique in the fact that it allows the measurement of unsteady interaction between the aerodynamics and the cooling, using a blowdown tunnel. ABB has discovered that ultrasonic signals can be used as nondestructive examinations to determine the degradation of TBC systems, and impingement cooling measurements have been obtained on a retrofitted ABB GT11N. Prototype measurements from the impingement testing show improvements of 10 percent and 2 percent for power output and thermal efficiency, respectively, could be achieved.

Fuel Flexibility. Fuel flexibility requirement of the ATS is being investigated with cycle analysis and combustion testing. The utility developers are performing studies to evaluate the benefits of ATS integration into coal-fired cycles, such as IGCC. Laboratory combustion studies are ongoing to evaluate fuel flexibility for industrial-scale ATS at the U.S. DOE's Federal Energy Technology Center (FETC) facility.

Environmental Superiority. To achieve single-digit NO_x emissions, all ATS developers are pursuing lean, premixed natural gas combustion systems. Lean, premixed combustors avoid the extremely high firing temperatures that produce thermal NO_x by thoroughly mixing fuel and air prior to combustion. Combustion instabilities (undesirable pressure oscillations) have become more pronounced, while burning very lean combustion mixtures. Research is focused to properly design combustion systems to eliminate the existence of combustion instabilities. FETC is currently evaluating active, as well as passive, methods to control combustion instabilities (Richards and Janus, 1997).

Catalytic combustion is an alternative approach under evaluation by several ATS developers. Ultra-low emissions, less than 5 ppm, have been achieved with catalytic combustors without flame instability or flame outs. Longer term testing of catalytic combustors is ongoing to determine its viability for use.

Reliability, Availability, Maintainability (RAM). Each of the turbine developers has incorporated a RAM assessment into their programs to ensure that their ATS has RAM equivalent to, or better than, current state-of-the-art systems. Utility advisory boards have been convened by the manufacturers to provide recommendations on design for the ATS. The majority of the recommendations are in the area of maintainability and system design to address reliability and simplification of the ATS (Cook and Schoenwald, 1996; McQuiggen, 1996). Potential application of current operations database programs to the ATS (Conway and Ekstrom, 1997) will drive RAM performance to the highest levels in the industry.

PHASE III -- TECHNOLOGY READINESS AND VALIDATION TESTING

Elements of the Phase III, Technology Readiness and Validation Testing Program, include detailed design and manufacturing of the ATS powerplants, performance analyses on ATS combined cycle and operation, and testing critical gas turbine components for design validation. The Phase III Utility Development Program focuses on validation and design of the advanced gas turbine combustor, compressor, and hot gas path components (Cook and Schoenwald, 1996; McQuiggen, 1996).

The ATS developers are deploying state-of-the-art aero/mechanical technologies that combine world-class performance with the durability demands of the land-based operating environment. This cross-functional, multidiscipline effort comprises a variety of organizations brought together in some of the most powerful development and marketing teams ever assembled. The critical decisions that have been made and the technical progress in engineering and design have reached a high degree of readiness for the subsystem testing and hardware purchases that are now under way. The progress has provided a sound basis for creating the strategic relationships that will bring each manufacturer's ATS to the market.

Test Programs

The Allison ATS approach provides unprecedented 40+ percent simple-cycle thermal efficiency at 13 MW. A compact and durable, high-pressure ratio (30:1), 2400 °F firing temperature and three shaft engine configuration provides this level of performance. The Allison development team has made significant progress towards the design of this advanced simple cycle engine. Layouts and the requisite supporting aerodynamic, dynamics, heat transfer, and stress analyses have led to the procurement of long lead parts. The high-pressure turbine is the most challenging portion of the ATS engine, with respect to achieving system efficiency goals, while providing the expected durability. Significant progress has been made in evaluating and testing the high cooling effectiveness of systems that will incorporate novel configurations of Castcool turbine technologies. A combustion sector rig will also test lean, premix combustion and catalytic combustion up to the rig pressure limit of 18 atmospheres and the ATS burner outlet design condition of 2450 °F. These technologies are critical components of Allison's highly efficient and clean, simple cycle ATS.

Allison has also identified a path to ATS commercialization. The ATS will be marketed commercially as the Allison 701-K. The approach provides the earliest possible commercial introduction at an acceptable risk. Significant interest by investor-owned utilities, independent power producers, and industry demonstrate confidence within the industry that the simple cycle ATS is a highly competitive solution to the U.S. and world's future power generation needs.

At the previous American Society of Mechanical Engineers Turbine Exposition in Orlando, Florida, Solar announced the Mercury 50, a single-shaft recuperated 5-MW turbine system for power generation applications. The technical approach for the Mercury 50 takes advantage of a wide variety of demonstrated technological advances, each providing sufficient margin to assure the superior durability and availability that are required by industrial gas turbine users. Within each selected technology, a combination of innovative primary and backup design solutions have been carefully blended to offer maximum cycle efficiency and emissions reductions with minimal risk.

For the recuperator, rig testing has verified the target recuperator effectiveness of 90 percent. Rig testing also verified performance following extended use of liquid fuels. The Mercury 50 incorporates Solar's latest generation of compressors, the ACE compressor. The operation of a full-scale test rig at the Compressor Research Facility, Wright-Patterson Air Force Base, Dayton, Ohio, confirms an efficiency improvement that is more than 2 points better than the compressors of Solar's current product line.

Fabrication of a half-scale turbine test rig has been completed and testing has been initiated to validate turbine performance. For low emissions on the Mercury 50, a Cooperative Research and Development Agreement with DOE's combustion facility at FETC has successfully leveraged Solar's commercial SoLoNOx® technology. Rig testing of a catalyst module was also completed.

Solar's commercialization plan has identified key markets within the Industries of the Future, where ATS products will provide substantial benefits. The plan also recognizes national policies and electric utility restructuring that may effect a movement toward distributed generation. The plan has created considerable interest in the Mercury 50. The identification of the first demonstration host site is expected shortly.

Under their H Development Program, GE has completed validation testing for the ATS compressor, turbine, and combustor.

Activities supporting the 9H (50 Hz) ATS are being performed under the GE program, while the 7H (60 Hz) activities are supported under the ATS Program. Scaled rig tests have been completed for the 9H, 18-stage compressor, and scaled tests are underway for the 7H compressor. Inlet aero, rotor cooling, and diffuser aero testing have also been completed.

The H Turbine Test Program focuses on evaluation of hot gas path internal and external heat transfer and material compatibility with steam-cooling fluids. GE is performing these tests to validate heat transfer design for the Stages 1 and 2 turbine nozzles, blades, and rotor. Tests rigs were instrumented with several static pressure taps and liquid crystal video thermography to measure the pressure distributions and heat transfer coefficients for the Stage 1 turbine nozzle. These results were incorporated into detailed three-dimensional (3-D) aero, thermal, and stress models to verify component life requirements. Further validation testing is being conducted with the Stage 1 nozzle cascade test stand located at the GE Aircraft Test Facility in Evendale, Ohio. This stand is being used for a 4-phase test program, which includes combustion system mapping, and nozzle aerodynamic, heat transfer, and low-cycle fatigue validation. Results of the test confirmed that steam cooling is as effective as predicted with overall temperatures in agreement with pre-test calculations.

Combustor-related accomplishments include a refinement of the GE dry, low NO_x design for more stable operation in the lean, premix mode, development of a full-scale test stand to validate combustor performance under H operating conditions and completion of reduced pressure laboratory tests.

Westinghouse is conducting an extensive technology development test program in the areas of combustion, heat transfer and cooling, aerodynamics, leakage control, and materials. Combustor cylinder flow mapping, flow visualization, and computational fluid dynamics have been utilized to optimize the engine performance. Optical diagnostic probes and combustion instability investigation are being used to measure pertinent parameters for low-emission combustor design. Both catalytic and lean, premix technology are being investigated as candidates for the Westinghouse ATS.

The Westinghouse ATS combustor is the piloted ring combustor, a design incorporating a pilot and two separate premixed zones arranged axially to the primary and secondary zones. The piloted ring combustor has also been incorporated into the 501G. This combustor is a premixed multistage design that produces ultra-low NO_x emissions with excellent stability.

To demonstrate the viability of ATS compressor performance, a full-scale compressor test will be performed at the U.S. Naval Yard in Philadelphia prior to full prototype engine testing. The compressor design is based on the Westinghouse 501G compressor, which uses the first 16 stages of the advanced turbine design. The aerodynamic design incorporates the latest 3-D viscous computer models and diffusion airfoil design. Aerodynamic model tests and hot cascade testing will be conducted to confirm the turbine closed-loop cooling design.

Active tip clearance control and brush seals are being designed to enhance the ATS engine efficiency with reduced air and hot gas leakage. Efficiency losses due to leakage around turbine internal parts are significant. Brush seals for the interstage area and abradable coating seals for the stationary shroud were developed under the DOE program to improve gas turbine thermal efficiency. These seals proved to be so successful that they were incorporated into the Westinghouse 501G design.

Materials Testing. Material steam compatibility and TBC tests have been completed under the GE H testing program. These tests provide the data to evaluate oxidation and mechanical property measurements in a steam environment and validate the cyclic life capability of the TBC under H conditions. The high gradient E-beam test facility has been utilized to test coated TBC specimens by replicating the surface temperature, thermal gradient, and stresses on steam-cooled components. TBC durability has been demonstrated for 2,400 cycles. Steam compatibility testing has been completed for component alloys, and no adverse effects of steam on material properties were identified.

Westinghouse is performing materials tests to determine comparative TBC longevity and effectiveness. Different TBC's and bond coats are being tested under field conditions and accelerated oxidation tests. New TBC's, developed under the DOE program, have found their way into the Westinghouse 501G design. Today, thermal wave imaging, a new inspection tool developed under the DOE program, can spot defects before they become a problem. Thermal wave imaging is now used in the factory and in field service for identifying defects in component coatings.

ATS Design and Manufacturing. Experience and techniques from aircraft turbine design technology are being used to develop reliable ATS products. Application of statistical design methods will minimize influence of design and manufacturing variability on product yield. In addition to data acquired from verification tests, field data is being incorporated into the design process.

Thin-wall, SX investment casting capability has been developed with casting suppliers. Production has begun to cast the largest SX components in the world for a gas turbine.

TECHNOLOGY BASE DEVELOPMENT

The University Consortium

The Advanced Gas Turbine Systems Research (AGTSR) Program is a collaborative university-industry research and development (R&D) consortium that is managed and administered by the South Carolina Energy R&D Center (Golan, 1996). AGTSR is a nationwide consortium dedicated to advancing land-based gas turbine systems for improving future power generation capability. It supports the technology-research arm of the ATS Program and targets industry-defined research needs in the areas of combustion, heat transfer, materials, aerodynamics, controls, alternative fuels, and advanced cycles. Presently, 90 performing member universities and 6 cost-sharing U.S. gas turbine corporations (Allison Engine Company, General Electric, Solar Turbines, Pratt and Whitney, Westinghouse, and Allied Signal) make up the consortium. Forty-one research projects are underway at member universities in the areas of materials, combustion, heat transfer, and aerodynamics. Nine workshops have been organized and hosted by the consortium, and 37 university student interns have been positioned at the member ATS companies. The AGTSR consortium nurtures close industry-university-Government collaboration to enhance synergism and the transition of research results, accelerate and promote evolutionary-revolutionary R&D, and to strive to keep a prominent U.S. industry strong, well into the 21st century. The AGTSR provides critical R&D support which has declined in the gas turbine industry over the last decade. Project highlights are given below:

- The University of California at Berkeley has developed a novel fiber optic probe with high frequency response for unsteady in-situ measurements of the fuel/air ratio in gas turbines pre-mixers and combustors. The probe was successfully tested at Solar Turbines and GE.
- Georgia Institute of Technology has developed a unique, open air combustion chemical vapor deposition process for producing TBC's. The results have indicated a 60 percent increase in furnace cycle test life as compared to other conventional techniques in applying TBC's.
- Syracuse University has developed 3-D inverse computer code to optimize turbo machinery design in advanced gas turbines. This code is being used for compressor design at Solar Turbines.
- Georgia Institute of Technology has developed a closed-loop control strategy for extending the lean flammability limit and eliminating combustion instability in gas turbine combustors. Their active control strategy was successfully demonstrated on a mid-scale combustor system in collaboration with the Westinghouse Science and Technology Center.

Materials and Manufacturing

Emphasis on increased efficiency and higher firing temperatures requires the use of improved materials with superior creep and thermal resistance characteristics. Casting development is underway for large, SX blades and vanes capable of meeting the stringent thermal gradients imposed by high firing temperature (2,600 °F) turbines. First-stage airfoils will be SX with directionally solidified or conventionally cast airfoils in subsequent stages. Additional thermal protection will be provided by TBC's applied to blades, vanes, and other components exposed to high temperatures. Oak Ridge National Laboratory, under sponsorship of the ATS Program, is managing contracts for airfoil manufacturing technology and TBC's.

Howmet Corporation and PCC Airfoils (Mueller, 1996; Kortovich,1996) are developing technology to reliably produce large, SX airfoils capable of meeting ATS requirements. Howmet is supported by a team, including ABB, Pratt & Whitney, Solar Turbines, Westinghouse, Aracor, and Purdue University. The project focuses on four areas -- low sulfur alloys, casting process development, post-cast process development, and casting defects tolerance definition. Key accomplishments include scaling up heats to 5000 pounds with sulfur levels less than 0.5 ppm, demonstrated capability to produce utility-sized, SX castings with no grain defects, development of prototype core materials and processes, and demonstration of a new inspection system for aero-sized blades, which is being scaled up to utility-sized blades.

PCC Airfoils is working with GE Power Generation and is evaluating alloy melt practices, modification, and improvement of SX casting processes, core materials and designs, and grain orientation control. PCC's major accomplishment is the development of a new low-cost process to remove sulfur from alloys. This will lead to lower equipment cost in industrial gas turbines and superior hot gas path component environmental resistance to oxidation.

Projects to develop advanced TBC's are underway at Westinghouse and Pratt & Whitney (Goedjen, 1996; Bornstein, et al., 1996). The goal of these projects is to develop dependable TBC's that enable increased turbine inlet temperatures, while maintaining airfoil substrate temperatures at levels to meet ATS life goals. TBC's will be developed with enhanced temperature capabilities over existing state-of-the-art coatings. Relative performance of bond coat systems, such as diffusion aluminides and overlay MCrAl-type compositions, is under evaluation. The effects of operating parameters of TBC application processes (e.g., electron beam-assisted physical vapor deposition and plasma spray processes) are being correlated to ceramic microstructure and thermal resistance. The performance of coatings will be evaluated by subjecting combinations of bond coats and ceramic layers to exposure tests intended to simulate the extreme corrosive and erosive environments to which actual components will be exposed. The most promising TBC's will be applied to airfoils which will be used in bench testing that reproduce the essential features (thermal gradients imposed by cooling) of first-stage blades and vanes. TBC systems that achieve the performance goals of the bench-testing phase will be applied to components that will be installed in actual operating engines. This optional phase of these projects will allow evaluation of TBC's over a 12-month period under actual engine conditions.

FETC

FETC's combustion group supports the university consortium (AGTSR) and provides technical evaluation of novel concepts generated both by small business and from internal sources (Casleton, 1996). FETC's internal research team resolves barrier technology issues using expertise that is resident within the FETC organization. To date, FETC has collaborated with various university investigators on projects involving low-emission combustor modeling, mixing sensor development, heat transfer sensor development, noise measurements in combustors, and various information exchanges on topics including combustor dynamics and control. FETC has assisted a small business to develop and test a novel porous burner which may provide a simple path to low-emission combustion in gas turbines. The problem of combustion oscillations has emerged as a critical problem for all ATS engine developers. FETC is using lab facilities in Morgantown, West Virginia, and Pittsburgh, Pennsylvania, to develop techniques to characterize and mitigate this problem. Ongoing work in FETC labs includes an experimental investigation of combustion under conditions expected in advanced humid air turbine (HAT) cycle engines.

Fuel Flexibility and Combustion Barrier Issues

Combustors for alternative fuels such as coal gas have been tested for IGCC powerplants. High-temperature desulfurization, or hot gas cleanup, offers many advantages over conventional low-temperature desulfurization processes but does not reduce the relatively high concentrations of fuel-bound nitrogen (FBN) that are typically found in low-Btu fuel. Tests with a full-scale rich-quench-lean (RQL) combustor (Feitelberg, 1996) demonstrated NO_x emissions as low as 50 parts-per-million-volume (on a dry, 15 percent oxygen basis), with 4,600 ppm of ammonia in the fuel. This corresponds to a conversion of about 5 percent ammonia to NO_x at a combustor outlet temperature of 2,100 ° to 2,200 °F. While this temperature is below ATS conditions, it indicates which proper design FBN conversion can be minimized through proper design using an RQL combustor.

Current activity has been focused on development of a humid air combustion turbine with United Technologies Research Center (UTRC) (Day, 1997). The objective of the project is to identify combustor configurations that will efficiently burn high-moisture, high-pressure gas/air mixtures and produce low emissions. Test data will be compared to computer models for design of full-scale engine combustors. An aero-derivative engine product developed by UTRC, the FT4000, is the base engine for this activity. The HAT development effort supports both the gas and coal-fired advanced cycles. Developments in aero-derivative engines are critical to achieving high-efficient, coal-fired systems, such as integrated gasification humidified air turbine and other FETC power systems products. Currently, computer models are being developed to aid in the design of combustor nozzles for testing at FETC. At FETC, shakedown testing of the initial nozzle design is underway.

FUTURE ADVANCEMENTS

The ATS Program is on schedule to have precommercial demonstrations operating in the year 2000. Phase III of the program is continuing with full-speed, no-load tests of the ATS utility-scale engines by the year 2000.

Future enhancements to gas turbines systems that offer benefits beyond the ATS Program are under consideration. Integrating fuel cells with gas turbines has the potential to offer systems with exceptionally high efficiencies, exceeding 70 percent. The second of two workshops on very high-efficiency fuel cell/gas turbine power cycles (Williams and Zeh, 1996) sponsored by DOE's FETC was held in August 1996. Significant interest to initiate development of integrated fuel cell/gas turbine systems was expressed by turbine manufacturers, fuel cell developers, and potential users of combined fuel cell/gas turbine systems. The potential to develop an advanced, flexible mid-size gas turbine was discussed at a workshop on March 4-5, 1997 (Layne and Hatfield, 1997). The workshop was also co-sponsored by the U.S. DOE, the California Energy Commission, the Electric Power Research Institute, the Gas Research Institute, the Gas Turbine Association, and the Collaborative Advanced Gas Turbine Program. The purpose of the workshop was to bring together a broad cross section of knowledgeable people to discuss the potential benefits, markets, technical attributes, development costs, and development funding approaches associated with making this new technology available in the commercial marketplace. The U.S. DOE, Office of Fossil Energy is assessing the feasibility of Vision 21, energy plants for the 21st century (U.S. DOE, 1997). The primary focus of Vision 21 is advanced power technology to create advanced fossil energy plants with a versatile capability of clean, high-efficiency power generation, electricity co-processing, co-production, and co-generation, and clean fuels and chemicals production. Advanced turbines will play a key role in meeting the overall goals of the Vision 21 plants.

The ATS Program established the objective for gas turbine systems to achieve greater than 60 percent system efficiency with superior environmental performance at a lower cost of electricity. Today, prototype ATS components are being manufactured and tested under turbine operating conditions. The ATS program is a major challenge on the threshold of reality and is a U.S. Government investment envied by foreign competitors. The marketplace is awaiting the commercialization of the ATS products. Thus, completion of the ATS program and successful prototype testing of the ATS is critical to sustain U.S. gas turbine industry dominance in the global marketplace.

DOE's Office of Energy Efficiency and Renewable Energy is developing crosscutting technologies for the industries of the future.

Industries of the future will benefit from continued advancements in gas turbine technology.

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