U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory

Advanced Turbine Systems

Advancing The Gas Turbine Power Industry

In 1992, the U.S. Department of Energy forged partnerships with industry and academia under the Advanced Turbine Systems (ATS) Program to go beyond evolutionary performance gains in utility-scale gas turbine development. Agreed upon goals of 60 percent efficiency and single digit NO_x emissions (in parts per million) represented major challenges in the fields of engineering, materials science, and thermodynamics—the equivalent of breaking the 4-minute mile.

Today, the goals have not only been met, but a knowledge base has been amassed that enables even further performance enhancement. The success firmly establishes the United States as the world leader in gas turbine technology and provides the underlying science to maintain that position.

ATS technology cost and performance characteristics make it the least-cost electric power generation and co-generation option available, providing a timely response to the growing dependence on natural gas driven by both global and regional energy and environmental demands.

Introduction

Through the Advanced Turbine Systems (ATS) Program, lofty visions in the early 1990s are now emerging as today's realities in the form of hardware entering the marketplace. An investment by government and industry in partnerships encompassing universities and national laboratories is paying significant dividends. This document examines some of the payoffs emerging in the utility sector resulting from work sponsored by the U.S. Department of Energy (DOE).

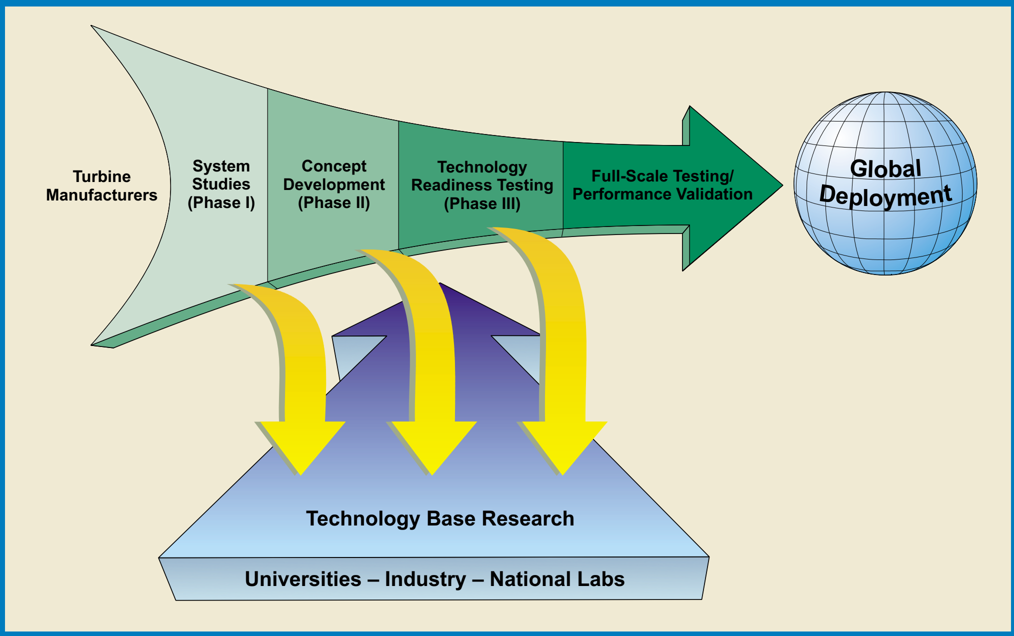
Both industrial and utility-scale turbines are addressed under the ATS Program. The DOE Office of Fossil Energy is responsible for the utility-scale portion and the DOE Office of Energy Efficiency and Renewable Energy is responsible for the industrial turbine portion. The focus here is on utility-scale work implemented under the auspices of the National Energy Technology Laboratory (NETL) for the DOE Office of Fossil Energy.

In 1992, DOE initiated the ATS Program to push gas turbine performance beyond evolutionary gains. For utility-scale turbines, the objectives were to achieve: (1) an efficiency of 60 percent on a lower heating value (LHV) basis in combined-cycle mode; (2) NO_x emissions less than 10 ppm by volume (dry basis) at 15 percent oxygen, without external controls; (3) a 10 percent lower cost of electricity; and (4) state-of-the-art reliability, availability, and maintainability (RAM) levels. To achieve these leapfrog performance gains, DOE mobilized the resources of leaders in the gas turbine industry, academia, and the national laboratories through unique partnerships.

The ATS Program adopted a two-pronged approach. Major systems development, under cost-shared cooperative agreements between DOE and turbine manufacturers, was conducted in parallel with fundamental (technology base) research carried out by a university-industry consortium and national laboratories.

Major systems development began with turbine manufacturers conducting systems studies in Phase I followed by concept development in Phase II. Today, one major system development is in Phase III, technology readiness testing, and another has moved into full-scale testing/performance validation. Throughout, the university-industry consortium and national laboratories have conducted research to address critical needs identified by industry in their pursuit of systems development and eventual global deployment.

ATS Program Strategy



Utility-Scale ATS Benefits

The ATS Program is meeting established objectives, laying a foundation for future advances, and providing a timely response to the burgeoning demand for clean, efficient, and affordable power both here and abroad. ATS technology represents a major cost and performance enhancement over existing natural gas combined-cycle, which is considered today's least-cost, environmentally superior electric power generation option. Moreover, ATS is intended to evolve to full fuel flexibility, allowing use of gas derived from coal, petroleum coke, biomass, and wastes. This compatibility improves the performance of advanced solid fuel technologies such as integrated gasification combined-cycle (IGCC) and second generation pressurized fluidized-bed. In summary, the ATS Program does the following:

- Provides a timely, environmentally sound, and affordable response to the nation's energy needs, which is requisite to sustaining economic growth and maintaining competitiveness in the world market
- Enhances the nation's energy security by using natural gas resources in a highly efficient manner
- Firmly establishes the United States as the world leader in gas turbine technology; provides the underlying science to maintain that leadership; and positions the United States to capture a large portion of a burgeoning world energy market, worth billions of dollars in sales and hundreds of thousands of jobs
- Provides a cost-effective means to address both national and global environmental concerns by reducing carbon dioxide emissions 50 percent relative to existing power plants, and providing nearly pollution-free performance
- Allows significant capacity additions at existing power plant sites by virtue of its highly compact configuration, which precludes the need for additional plant siting and transmission line installations
- Enhances the cost and performance of advanced solid fuel-based technologies such as integrated gasification combined-cycle and pressurized fluidized-bed combustion for markets lacking gas reserves

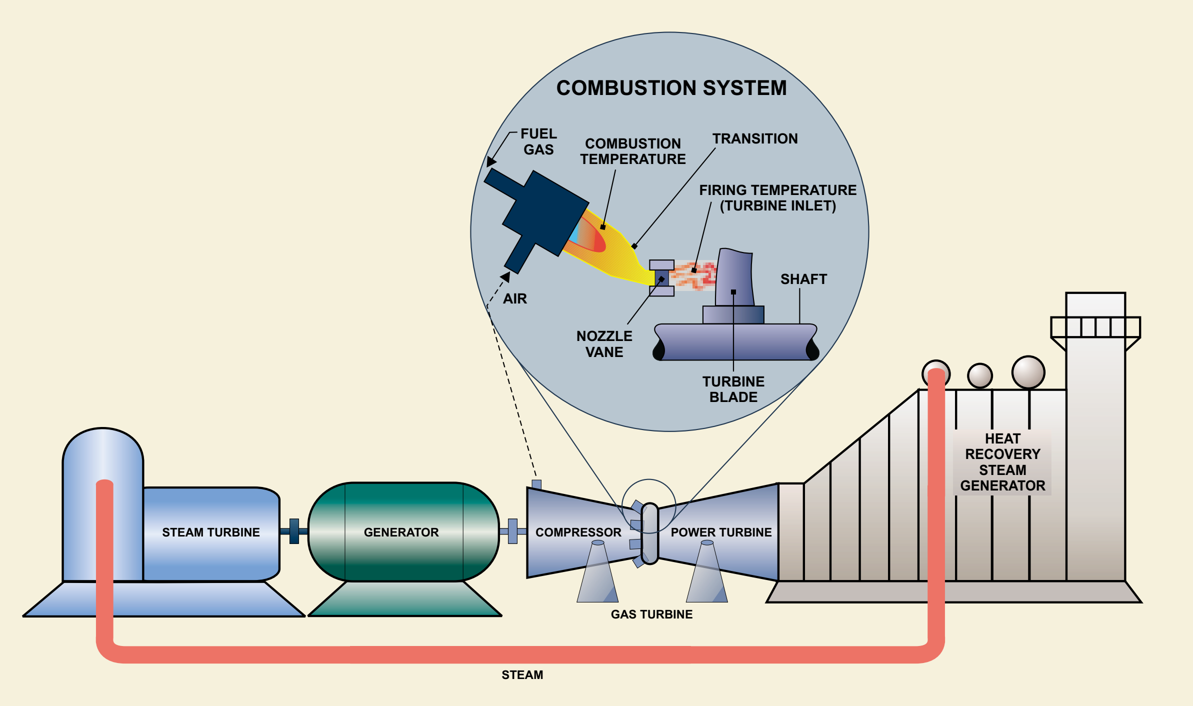
Gas Turbine Systems

A gas turbine is a heat engine that uses a high-temperature, high-pressure gas as the working fluid. Combustion of a fuel in air is usually used to produce the needed temperatures and pressures in the turbine, which is why gas turbines are often referred to as "combustion" turbines. To capture the energy, the working fluid is directed tangentially by vanes at the base of combustor nozzles to impinge upon specially designed airfoils (turbine blades). The turbine blades, through their curved shapes, redirect the gas stream, which absorbs the tangential momentum of the gas and produces the power. A series of turbine blade rows, or stages, are attached to a rotor/shaft assembly. The shaft rotation drives an electric generator and a compressor for the air used in the gas turbine combustor. Many turbines also use a heat exchanger called a recouperator to impart turbine exhaust heat into the combustor's air/fuel mixture.

Gas turbines produce high quality heat that can be used to generate steam for combined heat and power and combined-cycle applications, significantly enhancing efficiency. For utility applications, combined-cycle is the usual choice because the steam produced by the gas turbine exhaust is used to power a steam turbine for additional electricity generation. In fact, approximately 75 percent of all gas turbines are currently being used in combined-cycle plants. Also, the trend in combined-cycle design is to use a single-shaft configuration, whereby the gas and steam turbines are on either side of a common generator to reduce capital cost, operating complexity, and space requirements.

The challenge of achieving ATS targets of 60 percent efficiency and single digit NO_x emissions in parts per million is reflected in the fact that they are conflicting goals, which magnifies the difficulty. The road to higher efficiency is higher working fluid temperatures; yet higher temperatures exacerbate NO_x emissions, and at 2,800 °F reach a threshold of thermal NO_x formation. Moreover, limiting oxygen in order to lower NO_x emissions can lead to unacceptably high levels of carbon monoxide (CO) and unburned carbon emissions. Furthermore, increasing temperatures above the 2,350 °F used in today's systems represents a significant challenge to materials science.

Gas Turbine Combined-Cycle



General Electric Power Systems ATS Turbine

General Electric Power Systems (GEPS), one of two turbine manufacturers partnering with DOE to bring the ATS into the utility sector, has successfully completed initial development work, achieving or exceeding program goals. The resultant 7H ATS technology—a 400-MWe, 60 hertz combined-cycle system—is part of a larger GEPS *H System*™ program, which includes the 9H, a 480-MWe, 50 hertz system designed for overseas markets.

The *H System*™ is poised to enter the commercial marketplace. GEPS has fabricated the initial commercial units, the MS9001H (9H) and MS7001H (7H), and successfully completed full-speed, no-load tests on these units at GE's Greenville, South Carolina manufacturing facility. Having completed testing in 1999, the 9H is preceding the 7H into commercial service. The MS9001H is paving the way for eventual development of the Baglan Energy Park in South Wales, United Kingdom, with commercial operation scheduled for 2002. The MS7001H ATS will provide the basis for Sithe Energies' new 800-MWe Heritage Station in Scriba, New York, which is scheduled for commercial service in 2004.

Early entry of the 9H is part of the *H System*™ development strategy to reduce risk. The 9H incorporates critical ATS design features and provided early design verification. Also, because ATS goals required advancements in virtually all components of the gas turbine, GEPS incorporated its new systems approach for the *H System*™—the "design for six sigma" (DFSS) design process. DFSS accelerated development by improving up-front definition of performance requirements and specifications for subsystems and components, and by focusing the research and development activities. Downstream, the benefits will be improved reliability, availability, and maintainability due to integration of manufacturing and operational considerations into the DFSS specifications.

GEPS' 400-ton MS7001H in transit to full-speed, no-load testing

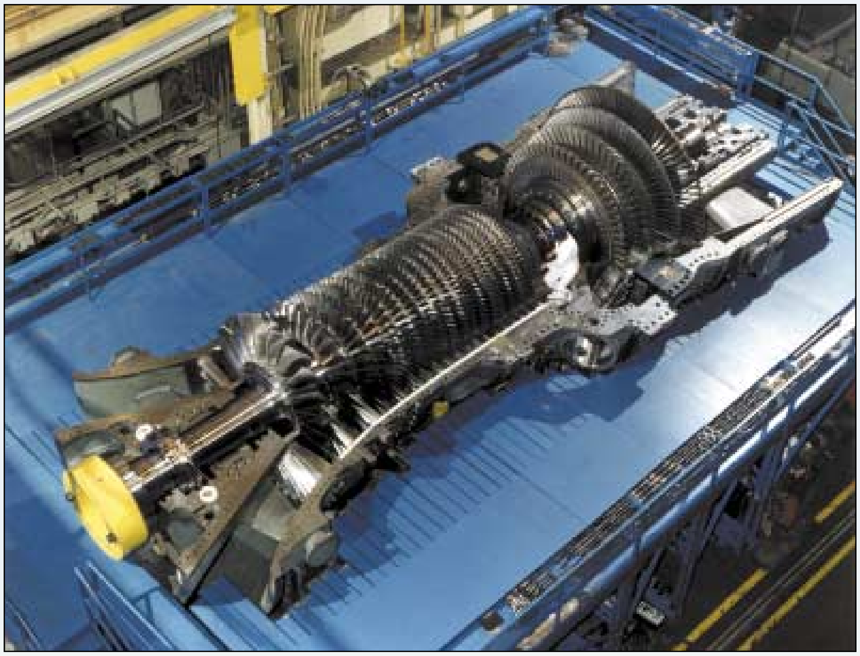
Meeting the Technical Challenges

Turbine

The need to address the conflicting goals of higher efficiency and lower NO_x emissions required systemic changes. The major driver was to increase the firing temperature (temperature into the first rotating turbine stage) without exceeding the NO_x formation combustion temperature of 2,800 ºF. To do so, GEPS introduced closed-loop steam cooling at the first and second stage nozzles and turbine blades (buckets) to reduce the differential between combustion and firing temperatures. The closed-loop steam cooling replaced open-loop air cooling that depends upon film cooling of the airfoils.

In open-loop air cooling, a significant amount of air is diverted from the compressor and is introduced into the working fluid. This approach results in approximately a 280 ºF temperature drop between the combustor and the turbine rotor inlet, and loss of compressed air energy into the hot gas path. Alternatively, closed-loop steam improves cooling and efficiency because of the superior heat transfer characteristics of steam relative to air, and the retention and use of heat in the closed-loop. The gas turbine serves as a parallel reheat steam generator for the steam turbine in its intended combined-cycle application.

The GEPS ATS uses a firing temperature class of 2,600 ºF, approximately 200 ºF above the most efficient predecessor combined-cycle system with no increase in combustion temperature. To allow these temperatures, the ATS incorporates several design features from aircraft engines.



General Electric's H System™ gas turbine showing the 18-stage compressor and 4-stage turbine

Single crystal (nickel superalloy) turbine bucket fabrication is used in the first two stages. This technique eliminates grain boundaries in the alloy, and offers superior thermal fatigue and creep characteristics. However, single crystal material characteristics contribute to the difficulty in airfoil manufacture, with historic application limited to relatively small hot section parts. The transition from manufacturing 10-inch, two-pound aircraft blades to fabricating blades 2–3 times longer and 10 times heavier represents a significant challenge. Adding to the challenge is the need to maintain very tight airfoil wall thickness tolerances for cooling, and airfoil contours for aerodynamics.

GEPS developed non-destructive evaluation techniques to verify production quality of single crystal ATS airfoils, as well as the directionally solidified blades used in stages three and four. Ultrasonic, infrared, and digital radiography x-ray inspection techniques are now in the hands of the turbine blade supplier. Moreover, to extend the useful component life, repair techniques were developed for the single crystal and directionally solidified airfoils.

Even with advanced cooling and single crystal fabrication, thermal barrier coatings (TBCs) are utilized. TBCs provide essential insulation and protection of the metal substrate from combustion gases. A ceramic TBC topcoat provides thermal resistance, and a metal bond coat provides oxidation resistance and bonds the topcoat to the substrate. GEPS developed an air plasma spray deposition process and associated software for robotic application. An e-beam test facility replicated turbine blade surface temperatures and thermal gradients to validate the process. The TBC is now being used where applicable throughout the GEPS product line.

Compressor

To meet *H System*™ air requirements, GEPS turned to the high-pressure compressor design used in its CF6-80C2 aircraft engine. The 7H system uses a 2.6:1 scale-up of the CF6-80C2 compressor, with four stages added (bringing it to 18 stages), to achieve a 23:1 pressure ratio and 1,230 lb/sec airflow. The design incorporates both variable inlet guide vanes, used on previous systems, and variable stator vanes at the front of the compressor. These variable vanes permit airflow adjustments to accommodate startup, turndown, and variations in ambient air temperatures.

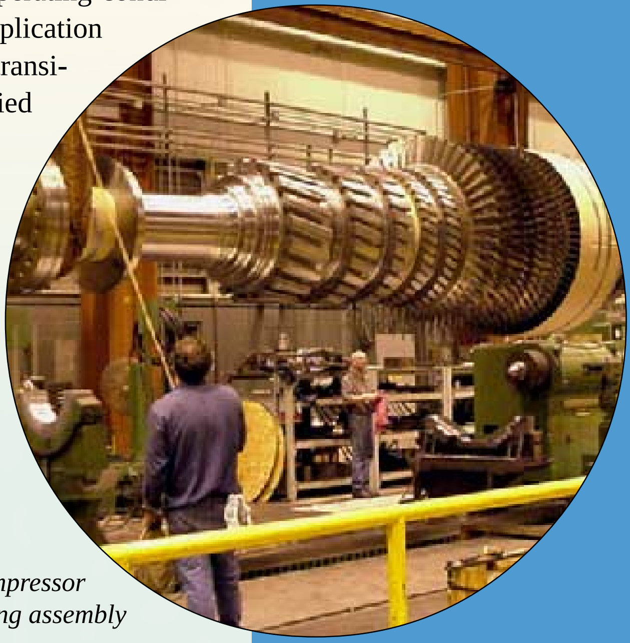
GEPS applied improved 3-D computational fluid dynamic (CFD) tools in the redesign of the compressor flow path. Full-scale evaluation of the 7H compressor at GEPS' Lynn, Massachusetts compressor test facility validated both the CFD model and the compressor performance.

H System™ compressors also circulate cooled discharge air in the rotor shaft to regulate temperature and permit the use of steel in lieu of Inconel. To allow a reduction in compressor airfoil tip clearance, the design included a dedicated ventilation system around the gas turbine.

Combustion

To achieve the single digit NO_x emission goal, the *H System*™ uses a lean pre-mix Dry Low NO_x (DLN) can-annular combustor system similar to the DLN in FA-class turbine service. The *H System*™ DLN 2.5 combustor combines increased airflow resulting from the use of closed-loop steam cooling and the new compressor with design refinements to produce both single digit NO_x and CO emissions.

GEPS subjected full-scale prototype, steam-cooled stage 1 nozzle segments to extensive testing under actual gas turbine operating conditions. Testing prompted design changes including application of TBC to both the combustor liner and downstream transition piece, use of a different base metal, and modified heat treatment and TBC application methods.



GEPS compressor rotor during assembly

Control System

The *H System*™ uses an integrated, full-authority, digital control system—the Mark VI. The Mark VI also manages steam flows between the heat recovery steam generator, steam turbine, and gas turbine; stores critical data for troubleshooting; and uses pyrometers to monitor stage 1 and stage 2 turbine bucket temperatures. The pyrometer system offers rapid detection of rises in temperature, enabling automatic turbine shutdown before damage occurs. The demonstrated success of the Mark VI has prompted GEPS to incorporate it into other (non-steam cooled) engines.

Energy Secretary Bill Richardson, flanked by Robert Nardelli of GE and South Carolina Senator Ernest Hollings, introduced GE's gas turbine at a ceremony in Greenville, South Carolina. Richardson stated: "This milestone will not only help maintain a cleaner environment, it will help fuel our growing economy, and it will keep electric bills low in homes and businesses across our country."

GE Power Systems has completed its work on the DOE ATS Program, and has achieved the Program goals. A full scale 7H (60 Hz) gas turbine has been designed, fabricated, and successfully tested at full speed, no load conditions at GE's Greenville, South Carolina manufacturing/test facility.

The GE *H System*™ combined-cycle power plant creates an entirely new category of power generation system. Its innovative cooling system allows a major increase in firing temperature, which allows the combined-cycle power plant to reach record levels of efficiency and specific work, while retaining low emissions capability, and with reliability parameters comparable to existing products.

The design for this "next generation" power generation system is now established. Both the 9H (50 Hz) and the 7H (60 Hz) family members are currently in the production and final validation phase. The extensive component test validation program, already well underway, will ensure delivery of a highly reliable combined-cycle power generation system.

Siemens Westinghouse Power Corporation ATS Turbine

Siemens Westinghouse Power Corporation (SWPC) has introduced into commercial operation many key ATS technologies. Operating engine demonstrations and ongoing technology development efforts are providing solid evidence that ATS program goals will be achieved.

In response to input from its customer advisory panel, SWPC is introducing advanced technologies in an evolutionary manner to minimize risk. As performance is proven, SWPC is infusing ATS technologies into commercially offered machines to enhance cost and performance and expand the benefit of the ATS program.

The first step in the evolutionary process was commissioning of the W501G. This unit introduced key ATS technologies such as closed-loop steam cooling, advanced compressor design, and high-temperature materials. After undergoing extensive evaluation at Lakeland Electric's McIntosh Power Station in Lakeland, Florida, the W501G entered commercial service in March 2000. Conversion to combined-cycle operation is scheduled for 2001.

The next step is integration of additional ATS technologies into the W501G, with testing to begin in 2003. The culmination will be demonstration of the W501ATS in 2005, which builds on the improvements incorporated in the W501G.

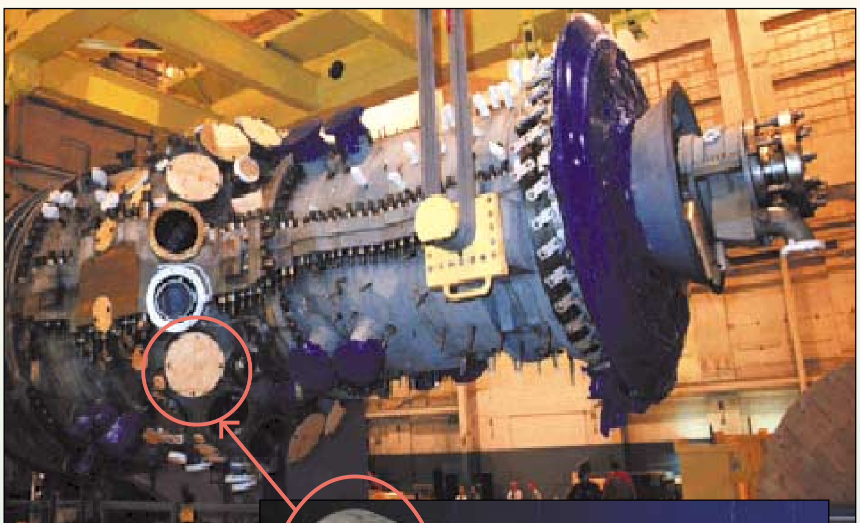
Leveraging ATS Technology

The following discusses the ATS technology introduced during commissioning of the 420-MWe W501G and currently being incorporated in other SWPC gas turbine systems. The combustion outlet temperature in these tests was within 50 ^{o}F of the projected ATS temperature.

Closed-Loop Steam Cooling

The W501G unit applied closed-loop steam cooling to the combustor "transitions," which duct hot combustion gas to the turbine inlet. Four external connections route steam to each transition supply manifold through internal piping. The supply manifold feeds steam to an internal wall cooling circuit. After the steam passes through the cooling circuit, it is collected in an exhaust manifold and then is ducted out of the engine.

Testing at Lakeland proved the viability of closed-loop steam cooling, and confirmed the ability to switch between steam and air cooling. The steam cooling clearly demonstrated superiority over air cooling.



Siemens Westinghouse W501G

Steam-cooled "transition"

Optimizing Aerodynamics

In parallel with W501G testing, SWPC validated the benefits of applying the latest three-dimensional design philosophy to the ATS four-stage turbine design. This was conducted in a one-third scale turbine test rig, incorporating the first two stages. SWPC conducted the testing in a shock tube facility at Ohio State University, which was instrumented with over 400 pressure, temperature, and heat flux gauges. An aerodynamic efficiency increase attributed to the use of "indexing" surpassed expected values.

High-Temperature TBCs

TBCs are an integral part of the W501ATS engine design. An ongoing development program evaluated several promising bond coats and ceramic materials prior to the W501G tests. The selected advanced bond coat/TBC system underwent 24,000 hours of cyclic accelerated oxidation testing at 1,850 °F. The W501G incorporated the selected TBC on the first and second row turbine blades. Plans are to incorporate the TBC system into other SWPC engines.

Compressor

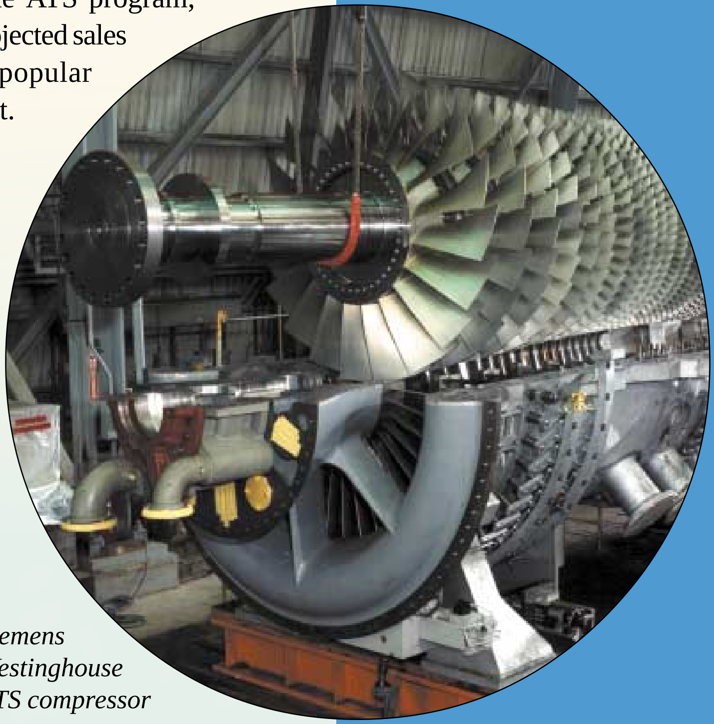
The W501G incorporates the first 16 stages of the 19 stage ATS compressor, designed to deliver 1,200 lb/sec airflow with a 27:1 pressure ratio. SWPC slightly modified the last three stages for the W501G compressor and changed vanes 1 and 2 from modulated to fixed. This resulted in air delivery at the ATS mass-flow rate of 1,200 lb/sec, but at a pressure ratio of 19:1, which optimizes the compressor for the W501G system.

The roots of the compressor design are in three-dimensional viscous flow analyses and custom designed, controlled-diffusion airfoil shapes. Controlled-diffusion airfoil design technology evolved from the aircraft industry. The airfoils emerging from these analytical methods are thinner and shaped at the ends to reduce boundary layer effects.

To verify the aerodynamic performance and mechanical integrity of the W501ATS compressor, a full-scale unit was manufactured and tested in 1997. SWPC confirmed performance expectations through extensive, highly instrumented tests in a specially designed facility at the Philadelphia Naval Base.

The ATS compressor technology has been retrofitted into the W501F product line using analytical techniques developed and proven under the ATS program. This significantly expands the benefit of the ATS program, given projected sales for this popular sized unit.

Aerodynamic redesign



Siemens Westinghouse ATS compressor

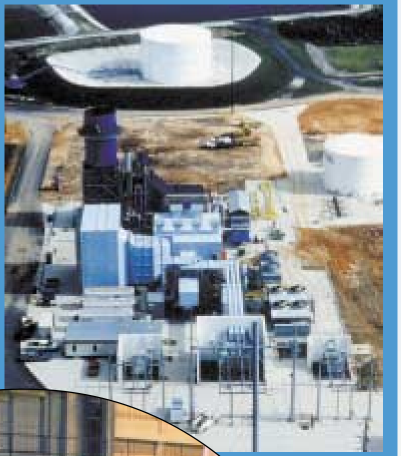
ATS Row 4 Turbine Blade

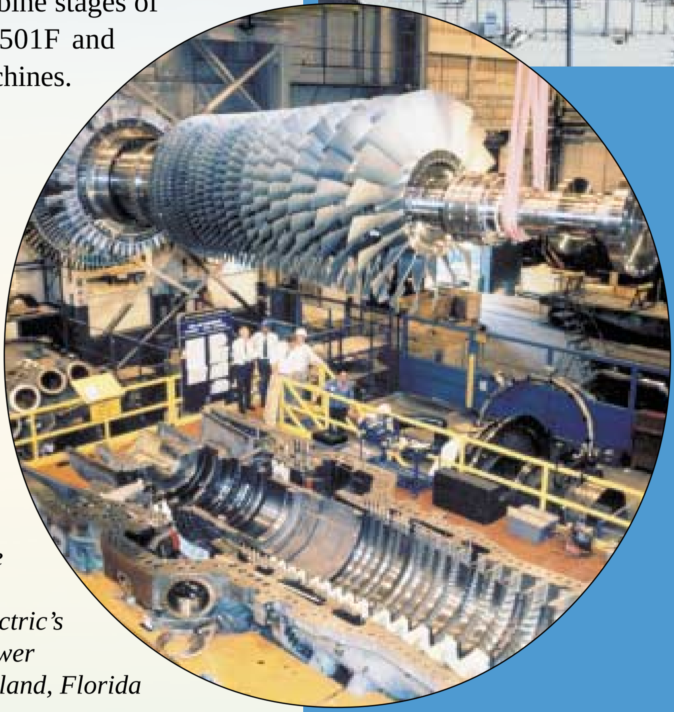
To accommodate the 25 percent increase in mass flow associated with the ATS compressor, the W501G uses the ATS Row 4 turbine blade assembly. The new design uses a large annulus area to reduce the exit velocity and capture the maximum amount of the gas flow kinetic energy before leaving the turbine. The uncooled ATS Row 4 turbine blade assembly met predicted performance levels throughout the W501G test program and established a new level in gas turbine output capability.

Brush Seals and Abradable Coatings

The W501ATS design applies brush seals to minimize air leakage and hot gas ingestion into turbine disc cavities. Seal locations include the compressor diaphragms, turbine disc front, turbine rims, and turbine interstages. SWPC used test rigs to develop effective, rugged, and reliable brush seals for the various applications. ATS compressor tests at the Philadelphia Naval Base verified brush seal low leakage and wear characteristics, which resulted in application of the seals to W501F and W501G product lines. Retrofitted units have demonstrated significantly improved performance.

Abradable coatings on turbine and compressor blade ring seals are also a part of the W501ATS design. This approach permits reduced tip clearances without risk of hardware damage, and provides more uniform tip clearance around the perimeter. Stage 1 turbine ring segment conditions present a particular challenge, requiring state-of-the-art thermal barrier properties while providing abradability. Engine testing verified the targeted abradability, tip-to-seal wear, and erosion characteristics. The coatings have been incorporated into the compressor and the first two turbine stages of both the W501F and W501G machines.





Siemens Westinghouse W501G at Lakeland Electric's McIntosh Power Station, Lakeland, Florida

Completing ATS Development

Development activities are focused on extending the W501G performance to ATS efficiencies by introducing additional technology advancements and increasing the firing temperature to 2,750 °F.

Closed-Loop Steam Cooling

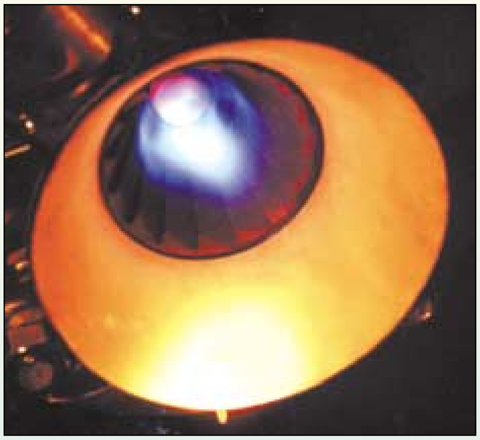
The next major step will be incorporation of closed-loop steam cooling into the W501G stage 1 turbine vane. This addition will extend the benefits of the existing steam cooled transition by eliminating cooling air at the turbine inlet, raising the firing temperature, and freeing more compressor air to reduce NO_x emissions.

Prior to retrofitting into the W501G, the ATS steam cooled vane underwent evaluation in a test rig incorporating a single full-scale combustor and transition capable of achieving ATS temperatures and pressures. The tests were conducted at the Arnold Air Force Base-Arnold Engineering Development Center in Tennessee. Instrumentation verified analytical predictions of metal temperatures, heat transfer coefficients, and stress. SWPC released the stage 1 turbine vane for manufacture and subsequent installation in the W501G, with testing scheduled for 2001.

Plans for the W501ATS are to incorporate closed-loop steam cooling into both stage 1 and stage 2 vanes and ring segments.

Catalytic Combustion

To achieve NO_x emission targets across a wide range of ATS operating conditions, SWPC is developing a catalytic combustor in conjunction with Precision Combustion, Inc. (PCI) under DOE's Small Business Innovation Research Program. Catalytic combustion serves to stabilize flame formation by enhancing oxidation under lean firing conditions. The SWPC/PCI piloted-ring combustor will replace the standard diffusion flame pilot burner with a catalytic pilot burner. Initial atmospheric pressure combustion testing determined turndown and emission characteristics. Follow-on tests successfully demonstrated catalytic combustion at full-scale under ATS combustion temperatures and pressures. Engine testing is planned for early 2001.



Catalytic pilot flame, which provides stability to the swirler flame

Materials

An active materials development program has been ongoing to support incorporation of single crystal and directionally solidified turbine blade alloys and steam cooling into the ATS design. The program has addressed the effect of steam cooling on materials, blade life prediction, advanced vane alloys, single crystal and directionally solidified blade alloy properties, and single crystal airfoil casting. Single crystal casting trials, using a CMSX-4 alloy on first stage vanes and blades, demonstrated the viability of casting these large components with their thin-wall cooling designs. But alternative manufacturing methods and alloys are being explored to reduce cost.

SWPC plans to use a new ceramic TBC emerging from the Oak Ridge National Laboratory Thermal Barrier Coatings Program—a part of the ATS Technology Base Program. The ceramic TBC, compatible with ATS temperatures, will be integrated with the new bond coat evaluated by SWPC earlier in the W501G tests.

Siemens Westinghouse is further expanding the benefits of the ATS program by introducing ATS-developed technologies into its mature product lines. For example, the latest W501F incorporates ATS brush seals, coatings, and compressor technology. Because the F frame accounts for a majority of current new unit sales, this infusion of technology yields significant savings in fuel and emissions.

Transferring Aerospace Technology to Land-Based Systems

As indicated in the General Electric and Siemens Westinghouse discussions, firing temperatures used in the ATS gas turbines necessitate materials changes in the hot gas path, particularly in the first two turbine stages. Moreover, new manufacturing techniques are needed to affect the materials changes. While single crystal and directionally solidified turbine blades are being used on aircraft engines, these parts are far smaller and one-tenth the weight of ATS utility-scale machines, and require less dimensional control.

To support the major systems development efforts, Oak Ridge National Laboratory has coordinated a materials and manufacturing technology program to hasten the incorporation of single crystal cast components into the ATS hot gas path.

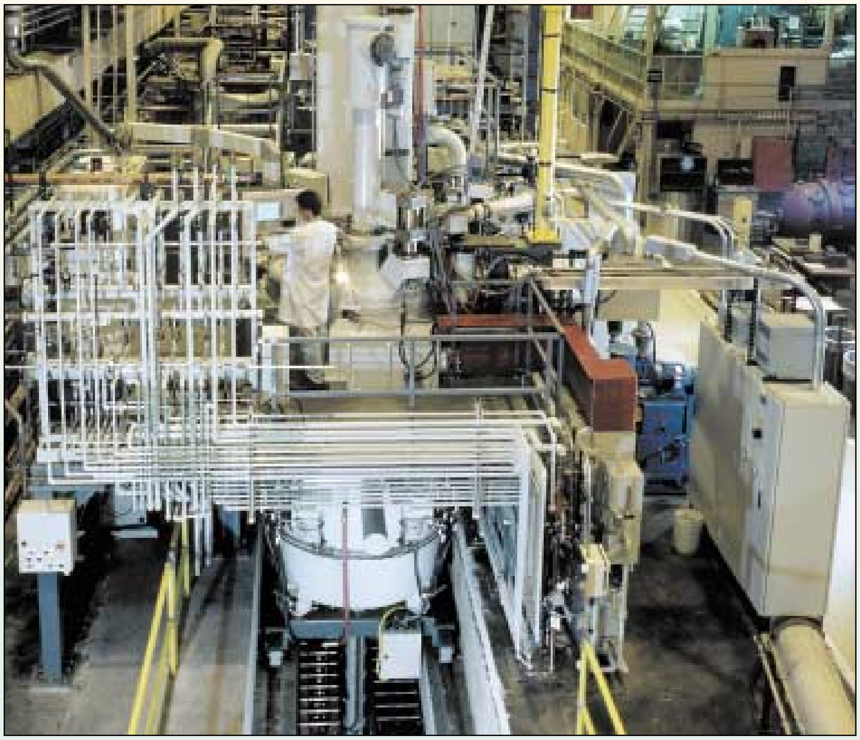
Single Crystal Casting

General Electric and PCC Airfoils (GE-PCC) teamed up to address the challenges of bringing cost-effective single crystal (SX) technology to land-based gas turbine engine applications. As noted by General Electric, the requirements for grain perfection and those for accurate part geometry compete with one another and create formidable challenges to successful, widespread use of large, directionally solidified (DS) and single crystal (SX) parts.

The GE-PCC work has produced a number of findings and advances in casting technology that will enable General Electric to incorporate higher-yield SX and DS components into their ATS unit. Early work determined that significant improvement in oxidation resistance resulted from reducing sulfur levels to 1.0–0.5 ppm in the super nickel alloy used. GE-PCC developed a low-cost melt desulfurization process to replace expensive heat treatment methods for sulfur removal.

In parallel, GE-PCC advanced the casting and silica core processes to enable SX manufacture of complex-cored and solid airfoils for land-based turbine applications. Also explored was the use of alumina ceramic formulated core materials to provide enhanced stability and dimensional control. Prototype testing showed promise for commercial application. Liquid metal cooling (LMC) was evaluated for application to DS processing. LMC provides increased thermal gradients without increasing the casting metal temperature by improving heat input and removal from castings. Casting of large stage-2 buckets for a 9G prototype machine was successfully demonstrated.

Siemens Westinghouse is developing a process to fabricate complex SX blades and vanes from small, readily producible castings using transient liquid phase bonding. Transient liquid phase bonding was developed in the 1970s by



General Electric's liquid metal cooling furnace

Pratt & Whitney for aircraft engine components. The bonding media contains a melting point depressant and a carefully selected subset of the parent metal chemistry to attain 90 percent of the base metal properties. In the fabricated component approach, bond planes are placed in insensitive locations.

Fabricated blade showing bonding plane

Siemens Westinghouse, in conjunction with the National Institute for Science and Technology (NIST), PCC, and Howmet, has moved the fabricated component approach to prototype production. Efforts have determined segments and bonding planes, developed coreless SX casting technology for the segments, developed fixtures to bond the segments, verified the structural integrity, and designed non-destructive evaluation (NDE) methods. Both fabricated stage 1 vanes and blades are to be used on the SWPC ATS unit.

Howmet Research Corporation is pursuing ways to enhance SX and DS casting technology toward improving yields for the large ATS hot gas path components. Activities are focused on: (1) improving current Vacuum Induction Melt (VIM) furnace capability and control; (2)

Fabricated blade, showing complexity of internals

addressing deficiencies in current shell systems; and (3) investigating novel cooling concepts for increased thermal gradients during the solidification process.

The thrust of the VIM furnace efforts is definition of the factors that will improve control of mold temperatures and thermal gradients. Howmet conducted furnace surveys on the GEPS 9H blade casting process to update and validate a solidification process model. Computer models were also developed to analyze potential and current furnace materials. These models will provide the tools to optimize the VIM furnace design. Howmet has demonstrated that improvements of up to 40 percent in the thermal gradient are attainable by enhancing the current system.

The shell systems activities address the additional requirements imposed on the ceramic mold with increased casting size. For example, longer casting times induce shell creep, thicker shells reduce thermal gradients, and the larger and heavier molds lead to structural and handling problems. Howmet investigated materials additives to strengthen the shell, and additives to improve thermal conductivity. Under some conditions, additives reduced creep deflection by 25–90 percent. Similarly, material additives achieved improvements in thermal conductivity of up to five times under some conditions.

As indicated above, maintaining a high thermal gradient at the solidification front is critical to preventing casting defects and enhancing yields. Novel cooling methods have the potential for achieving revolutionary increases in thermal gradients. The research being carried out is defining the heat transfer mechanisms necessary to design such novel cooling methods. Work to date has shown that the maximum thermal gradient may be limited by three rather than one resistance mechanism. By identifying the principal rate limiting thermal characteristic, a significant increase in thermal gradient may be achieved.

The advances in materials and manufacturing technology needed to effectively transfer aerospace technology to the large land-based turbine systems represented the single greatest challenge to meeting ATS goals. Only through mutual investments in extensive R&D under ATS partnerships was the challenge successfully met and a foundation laid for further advancement.

Advancing Combustion Technology Through NETL Partnerships

NETL conducts combustion research in partnership with industry and university-industry consortia to address the challenges associated with achieving substantial gains in efficiency and environmental performance, and expanding fuel options for gas turbines. As discussed previously, moving to higher temperatures and pressures for efficiency improvement conflicts with the need for low emissions. Using new gas turbine cycles and operating on lower energy density renewable or opportunity fuels introduce additional demands on combustion.

To address combustion challenges, NETL's on-site research supports the ATS program by developing and evaluating new technology for ATS applications. The NETL laboratories have provided public data on various issues associated with low-emission combustion, including the stability behavior of low-emission combustion, novel combustor concepts, and combustion in new engine cycles.

The NETL research is often carried out through partnerships with industrial or academic collaborators. Cooperative Research and Development Agreements (CRADAs) can be used to protect participants' intellectual property, while other approaches such as sharing public data have produced benefits to the various members of the turbine community. The following activities exemplify NETL's gas turbine research.

Surface Stabilized Combustion

NETL teamed with Alzeta Corporation to investigate a new approach to ultra-low-NO_x (2 ppm or less) combustion under high temperature and pressure regimes—Surface-Stabilized Combustion (SSC). The Low Emissions Combustor Test and Research (LECTR) facility at NETL provided the test platform for the investigation. LECTR is readily adaptable to a variety of combustor designs, and is capable of delivering representative gas turbine temperatures and pressures.

SSC may offer improved performance compared to existing DLN combustors, which use high excess air levels to reduce flame temperatures and thus NO_x emissions.

The SSC DLN burner uses a thin, compressed, and sintered porous metal fiber mat (Pyromat) at the burner inlet to stabilize combustion. The Pyromat stabilizes combustion by maintaining the presence of a high-temperature surface in the fuel-air flow path.

Testing at NETL defined the key parameters and operating envelope, and refined the design. Subsequent testing in conjunction with Solar Turbines validated ultra-low-NO_x and low CO emissions performance, further developed the hardware, and positioned the technology for commercialization.

NETL Dynamic Gas Turbine Combustor

Macrolaminate fuel injector array, shown here after testing, is used for dual-fuel applications – Photo courtesy of Parker Hannifin

Humid Air Combustion

The Humid Air Turbine (HAT) cycle is an advanced gas turbine cycle in which water-saturated air is introduced along with gaseous fuels, and is combusted at high pressure. Projected advantages are reduced NO_x, and enhanced power output gained by increasing mass flow through the turbine. The HAT cycle could potentially provide a low-cost option for power generation, with high thermal efficiency and rapid startup time.

A NETL partnership with United Technologies Research Center and Pratt & Whitney addressed actual HAT cycle combustion characteristics using the LECTR facility. A unique method to produce coincident ultra-low-NO_x and CO levels was found in tests of an air-cooled combustion liner. The results were used to further develop HAT cycle modeling efforts. Previous investigations on the HAT cycle had largely been limited to systems and modeling studies.

Duel-Fuel Combustion

Many gas turbine installations require operation on both liquid and gaseous fuels without affecting operability or environmental performance. Liquid fuels are more difficult to mix and pose difficulties in achieving the homogeneous fuel-air mixture distribution that is needed for low-NO_x combustion.

Under a CRADA, NETL and Parker Hannifin evaluated a novel dual fuel pre-mixer concept using a manufacturing technique called “macrolamination.” This technique allows complex internal flow channels to be formed by etching them into thin substrates and bonding the substrates together to form fuel injector arrays.

Testing at NETL showed that the Parker Hannifin pre-mixer enabled comparable environmental performance with both natural gas and type 2 diesel fuel at representative temperatures and pressures.

Stabilizing Combustion Dynamics

Combustion oscillations (or dynamics) continues to be a challenging issue for the design of low-emissions combustors. Oscillations often complicate achievement of emissions goals, or limit engine capability for new fuels or new requirements. To address this issue, NETL has conducted various research projects to identify methods to improve combustion stability. These investigations have identified important time scales that can be modified to improve combustion performance. In partnership with the Pittsburgh Supercomputing Center, NETL has explored the dynamic structure of turbine flames. The results are being used to understand how the dynamic combustion response can be modified to enhance stability. In addition, through an AGTSR award, Virginia Tech has conducted a series of acoustic tests in the NETL facilities that have demonstrated promising methods to evaluate the acoustic response of turbine combustors. Methods to measure both the acoustic and combustion responses are vital to enhance the stability of low-emission combustors and achieve the goals of tomorrow’s advanced combustion systems.

Another promising approach to enhance combustion stability is called “active” dynamics control. Active control pulses the fuel to release heat out-of-phase relative to the oscillation. Through a CRADA, NETL and Solar Turbines recently explored a variation of active combustion dynamics control, called periodic equivalence ratio modulation (PERM). In applying PERM, adjacent injectors alternately inject fuel at a modulated frequency. This modulation serves to dampen pressure pulses from any particular injector, while maintaining a desired time-averaged fuel-air ratio (equivalence ratio). Testing on a 12-injector engine showed that PERM effectively eliminated a 3-psi peak-to-peak pressure oscillation. Modulation was carried out at frequencies from 10 to 100 hertz without noticeable effect on engine performance.

Establishing the Scientific Foundation for the 21st Century Gas Turbine

Anchoring ATS efforts to provide the underlying science (technology base research)—requisite for major systems developments—is the Advanced Gas Turbine Systems Research (AGTSR) Program. AGTSR is a university/industry consortium that has grown into a vibrant virtual laboratory with national scope and worldwide recognition. Since its inception in 1992, AGTSR has networked the participation of 100 universities in 38 states, and 10 major players in the gas turbine industry. Through networking research activities, AGTSR has exponentially increased the interactions among researchers and interested parties, breaking the mold of traditional one-on-one university research (researcher and funding agency). Moreover, AGTSR has not only established a body of scientific excellence in gas turbine technology, but provided for continued U.S. leadership in turbine technology through an ongoing education program.

With DOE oversight and industry guidance, the South Carolina Institute for Energy Studies (SCIES) administers the AGTSR Program, providing the linkage between universities, industry, and government. A 10-member Industry Review Board (IRB) provides corporate leaders who define the thrust of the research program and technical experts to evaluate research proposals. IRB membership includes gas turbine manufacturers, parts suppliers, customers, and industry research and development organizations. SCIES coordinates the research efforts, creates teams of excellence in the various fields of endeavor, conducts workshops, and arranges internships and fellowships as part of an education program.

Research remains the primary mission of AGTSR. But as the program matured, other functions emerged as a consequence of the program's success. Workshops became necessary for effective technology transfer. And education activities became a natural outgrowth to sustain scientific excellence, such as internships, fellowships, faculty studies, and special studies. To date, 16 separate universities around the country have sponsored workshops on key topics. All interns were eventually employed by the gas turbine industry or by a university. Well over 400 university personnel and over 100 industry experts have participated directly in the AGTSR program.

The structure of AGTSR serves to ensure the quality, relevance, and timeliness of the research. The quality of research is assured by university peer review at workshops and through the publication process. Relevance of the research is established by having industry define the research needs, select the research, and critique the results. Timeliness is guaranteed by industry and DOE involvement with Performing Member institutions throughout the life of the projects.

The creation of a national network of universities under AGTSR mobilized the scientific talent needed to understand the fundamental mechanisms impeding gas turbine performance gains and to identify pathways for overcoming them.

AGTS professor and graduate student reviewing progress on their project

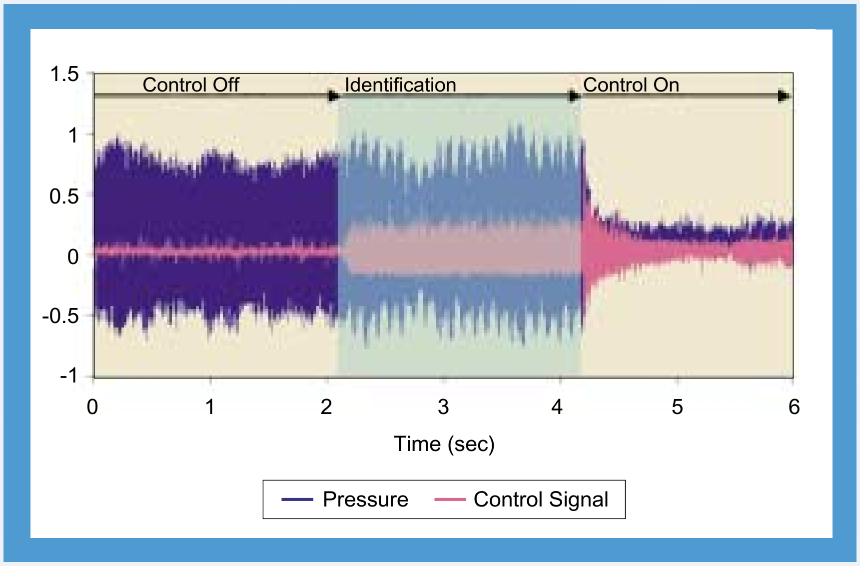
Examples of Success

The successes in the AGTSR program are too numerous to recount. The following examples are offered to exemplify the work carried out in the three program areas.

Combustion

Instability Control for Low Emissions Combustors—*Georgia Tech*. Gas turbine design today incorporates lean pre-mix combustion to reduce NO_x emissions. Effective mixing of the high volume of air with the fuel for lean combustion is difficult and often leads to combustion instability that can cause vibration and damage, or turbine shutdown. Georgia Tech developed an automatic means to actively detect the onset of combustion instabilities, identify combustion characteristics, and "instantaneously" attenuate the unstable mode. Georgia Tech first fabricated a low-NO_x gas turbine simulator to develop the Active Control System. Siemens Westinghouse carried out successful verification testing on a full-scale 3-MW gas turbine combustor. The observed four-fold reduction in amplitudes of combustion pressure oscillations represents a major milestone in the implementation of active combustion control. Two patents have been issued on the Georgia Tech technology, a third is pending, and the technology is being transferred to industry. NASA has purchased an Active Control System for testing.

Computer Code Improvements for Low Emission Combustor Design—*Cornell University*. It is crucial for low emission turbine combustor design codes to accurately predict NO_x and CO emissions. To date, computer codes used for combustor emission design have either impractically long run times, or have unacceptable computational inaccuracies. Cornell University has improved significantly upon an *in situ* adaptive tabulation (ISAT) algorithm, which reduces computer computation times for combustion chemistry by a factor of 40. In controlled piloted jet flame validation tests, the improved ISAT accurately predicted NO_x and CO levels, as well as local extinction and re-ignition. At least one gas turbine manufacturer has already incorporated the improved ISAT algorithm into their combustor design system.



Active Control System identifies combustion instabilities and instantaneously attenuates the unstable mode

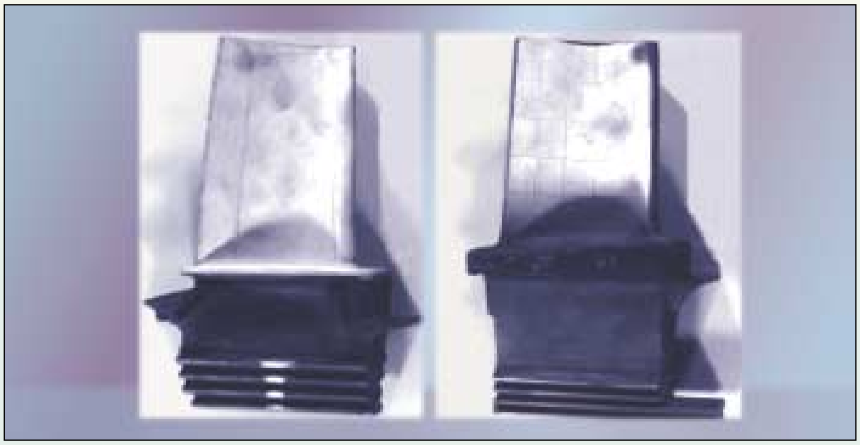
Aerodynamics and Heat Transfer

Advanced Component Cooling for Improved Turbine Performance—*Clemson University*. Materials and air cooling techniques—used in the past to enable high turbine inlet temperatures and resulting performance benefits—are approaching limits of diminishing returns. Accordingly, General Electric and Siemens Westinghouse are using steam cooling for their very high temperature ATS turbines. Clemson University has conducted experiments in four test configurations to show that steam cooling performance is substantially improved by adding small quantities of water mist. Depending on the test configuration, an addition of 1 percent (by weight) of mist typically enhanced cooling heat transfer by 50–100 percent, and in best cases, by as much as 700 percent. By quantifying the potential benefits and defining key parameters, Clemson has provided the scientific underpinning to support development of a next generation closed-loop cooling system.

Simplified Method for Evaluating Aerodynamic Interactions between Vane/Blade Rows—*Massachusetts Institute of Technology*. Reducing efficiency losses, due to aerodynamic interactions between adjacent rows of stationary vanes and rotating blades, is another important approach to improving gas turbine performance. However, the computer codes that are capable of aerodynamic analyses of the unsteady effects and complex geometry of adjacent airfoil rows require extensive manpower efforts to set up, multiple computer runs, and very long run times. Such analyses often require resources and time in excess of those available for a turbine development program. In a project coordinated with Solar Turbines, Massachusetts Institute of Technology (MIT) has been developing a relatively simple aerodynamics analysis approach to represent the unsteady effects on compressor rotor blades resulting from their relative motion with respect to the downstream stationary stator vanes. MIT has conducted computer aerodynamic analyses to show that this unsteadiness effect is negligible and the downstream stators can be represented by a time-averaged pressure profile for the conditions analyzed. MIT is now seeking to delineate the general conditions under which this observation holds. For those conditions, the significance of the MIT results is that multiple expensive computer runs representing adjacent blade-vane rows will not be needed to determine rotor aerodynamic performance. Only a single run, using a time-averaged downstream pressure profile, is needed.

Non-Destructive Evaluations of Thermal Barrier Coatings—*University of Connecticut* and *University of California, Santa Barbara*. The University of Connecticut (UCONN) and University of California, Santa Barbara (UCSB) are developing NDE methods for TBCs. NDE methods are needed to improve TBC manufacturing quality and operational lifetime inconsistencies, which have impeded the full implementation of the turbine power and efficiency benefits derived from TBCs. The need is so great and the results from a past AGTSR project are so promising that several of the U.S. gas turbine manufacturers, a coating supplier, and an instrument maker are providing a substantial in-kind and direct cost-share for this current AGTSR project. One expected output from this project is a low-cost and portable prototype NDE instrument for TBCs, which will be used by turbine manufacturers, overhaul facilities, and coating suppliers. In separate coordinated efforts, UCONN and UCSB are using laser techniques differently for NDE evaluations. UCONN uses laser techniques to measure stresses in coated laboratory specimens cycled to failure and coated engine parts from the field. Correlation of the laser signals with TBC stress degradation is used to assess remaining TBC life. UCSB complements laser measurements of degraded materials properties with mechanistic modeling to predict remaining life. Both projects have demonstrated laser signal correlation with life-affecting properties.

Small-Particle Plasma Spray TBCs—*Northwestern University*. Northwestern University has demonstrated a small-particle plasma spray (SPPS) process to produce novel TBCs. SPPS allows small particles to be placed into the plasma in a more controlled manner to reduce powder vaporization and produce less open porosity. Multiple micrometer thick layers are used in lieu of a single coat to enhance toughness. Also, graded porosity can be applied to enhance thermal conductivity and elastic properties. Testing has shown both improved thermal conductivity and oxidation resistant behavior.



As-Deposited Engine Tested

Laser fluorescence testing in support of NDE development at UCONN & UCSB

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Wichita State University
Worcester Polytechnic Institute
Wright State University
University of Wyoming
Yale University

AGTSR Industrial Project Partners

There are ten industrial turbine developers participating in the project. Each company contributes $25,000 (non-voting $7,500) a year to the program.

- EPRI (non-voting)
- General Electric Power
- Honeywell Engine Systems
- Parker Hannifin (non-voting)
- Pratt & Whitney
- Rolls-Royce Allison
- Solar Turbines
- Southern Company Services (non-voting)
- Siemens Westinghouse
- Woodward FST (non-voting)

Taking the Next Step

The ATS Program by any measure is a resounding success. Much of the technology developed under the Program is already being incorporated into existing products and two 400-MWe ATS units are poised to enter commercial service. Revolutionary goals set in the early 1990s have been met or surpassed. This accomplishment, while proving the skeptics wrong, further substantiated the tremendous potential inherent in mobilizing the nation's best talents to achieve difficult strategic objectives.

Another related challenge awaits. Gas turbines are being called upon to meet other strategically important market needs. Utility restructuring, increasingly stringent environmental regulations, and a growing demand for peaking power, intermediate duty, and distributed generation are combining to establish the need for a next generation of turbine systems. The market is quite large and the payoff in environmental and cost-of-electricity benefits are great through improvements in efficiency and reduction of emissions levels, particularly with the 50-year replacement cycle. But competitive forces embodied in utility restructuring that are driving this market need are also making it difficult for the power industry to invest in high risk research and development.

The time is right for a Next Generation Turbine Program that again mobilizes the nation's best talents, but for a different set of needs. Intermediate sized *flexible turbine systems* will be required to operate effectively over a wide range of duty cycles, with a variety of fuels, while achieving 15 percent efficiency and cost-of-electricity improvements. To achieve greater than 70 percent efficiency, the challenge of developing *Turbine/Fuel Cell Hybrids*, a whole new cycle, will have to be undertaken. These leapfrog performance goals are made possible by the technological advances achieved under the ATS Program, coupled with the experience gained in forging private-public partnerships with industry, academia, and the national laboratories.

Next Generation Turbine Program

The Department of Energy has launched the Next Generation Turbine (NGT) Program in response to needs identified in market and public benefit analyses and workshops structured to obtain stakeholder input.

The NGT Program addresses the challenges of:

- Providing continued energy security through reduced fuel consumption and dependence on imported fuel supplies;
- Protecting citizens from the threat of pollution and global climate change through major efficiency and environmental performance gains; and
- Ensuring that the nation's electricity supply system remains affordable, robust, and reliable through lowering life-cycle costs and advancing reliability, availability, and maintainability (RAM) technology.

There are three elements in the NGT Program:

- **Systems Development and Integration** includes the government-industry partnerships needed to develop low-cost, fuel and duty flexible gas turbines and hybrid systems that are responsive to the energy and environmental demands of the 21st century.
- **RAM Improvements** provide the instrumentation, analytical modeling, and evaluation techniques necessary to predict impending problems and establish maintenance requirements based on gas turbine operational characteristics.
- **Crosscutting Research and Development** provides the underlying science in combustion, materials, and diagnostics needed to support new technology development.

Benefits will include:

- Conservation of natural resources (water and land);
- Reduced air emissions (CO_2, NO_x, SO_x);
- Lower primary energy consumption (oil, coal, or natural gas depending on the region);
- Lower cost-of-electricity;
- Improved system reliability;
- Improved competitiveness in the world market; and
- Job creation.

For More Information

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