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# THE SIEMENS WESTINGHOUSE ADVANCED TURBINE SYSTEMS PROGRAM

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**Abstract**

The Siemens Westinghouse Advanced Turbine System (ATS) has the ultimate goal of achieving greater than 60% LHV-based net plant thermal efficiency, less than 10 part per million NOx emissions, a 10% reduction in cost or electricity, and reliability-availability-maintainability (RAM) equivalent to modern advanced power generation systems. The ATS program, which is supported by the U.S. Department of Energy, introduces advanced technologies in three evolutionary steps to minimize risks and to increase the net benefits of the program. First, the W501G (currently in commissioning with first commercial release March 2000) introduces many ATS technologies such as closed-loop steam cooling, advanced compressor design, and high temperature materials. Concurrently, Siemens Westinghouse is infusing ATS technologies into its mature frames. From the W501G, steam-cooled turbine vanes, leakage improvements, and increased burner temperature are added. Finally, the W501ATS engine builds on

these improvements which reduces development risk. Testing to date has demonstrated that ATS Program goals are obtainable, and results have been incorporated into the W501ATS design.

## INTRODUCTION

The Advanced Turbine Systems Program (ATS) co -funded by the U.S. Department of Energy, Office of Fossil Energy, is an ambitious multi-year effort whose goal is to develop technologies necessary for achieving significant increase in natural gas-fired power generation plant efficiency, a decrease in cost of electricity, and a reduction in harmful emissions, while maintaining the current state-of-the-art reliability, availability, and maintainability (RAM) levels.

The Siemens Westinghouse ATS plant incorporates an enhanced technology gas turbine design; a new three-pressure level, two-casing steam turbine design; and a high efficiency generator. To achieve the ATS Program goals for performance, emissions, electricity cost, and mechanical reliability, significant advancements were required in key technologies applied in gas turbine design. Successful developments were carried out in technologies relating to aerodynamics, combustion, cooling, sealing, materials, and coatings.

The W501ATS engine incorporates new technologies, as well as proven design features developed over the last 50 years and employed successfully in the W501 series of heavy-duty industrial and utility engines. These proven design features include single-shaft, two-bearing rotor; cold-end generator drive; compressor blade rings; low-alloy-steel rotor discs; curvic-clutched turbine rotor; four-stage turbine; cooled and filtered rotor cooling air; single first-stage turbine vane segments; tangential exhaust struts; and individual combustor baskets. The W501ATS engine is the latest in successful designs evolving from proven predecessors such as the 186 MW W501F and the 250 MW W501G.

## EVOLUTIONARY APPROACH

Siemens Westinghouse solicits input from an industry advisory panel comprised of members from major U.S. and international utilities and independent power producers. Based on the input from this panel and market analyses, Siemens Westinghouse is pursuing an evolutionary introduction of the ATS, which introduces the ATS-technology in stages culminating in an engine that meets or exceeds all of the program objectives. This approach has two main advantages. First, the evolutionary approach mitigates the risk associated with introducing multiple, advanced technologies simultaneously. Second, the early introduction of ATS technology expands the net benefit of the program, as compared with limiting the technologies to only the ATS engine.

The evolutionary approach is shown schematically in Figure 1. First, the introduction of the ATS frame begins with the W501G. Many ATS technologies are incorporated in the W501G and are discussed later. Next, steam-cooled turbine vanes, leakage improvements, and increased burner temperature are added to the W501G. Finally, the W501ATS engine builds on these improvements which reduces development risks through early demonstration of many critical technologies.

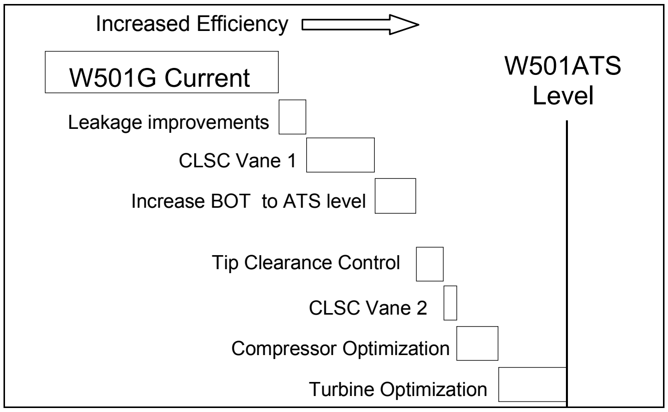


Figure 1. Evolutionary approach leading to the ATS engine

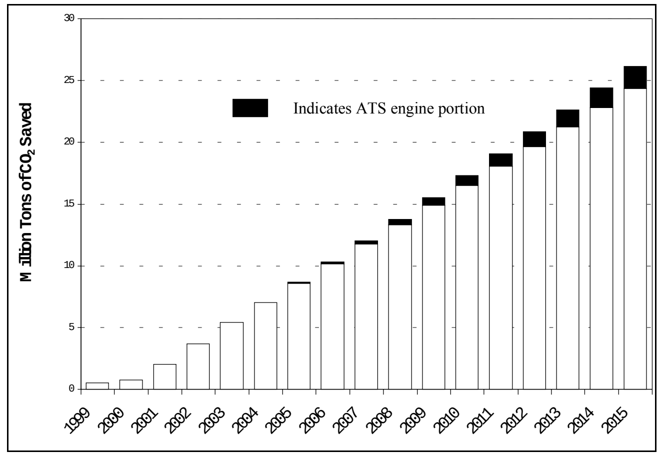


Figure 2 - $CO_2$ savings from ATS Technology

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-developed brush seals, coatings, and compressor technology. Furthermore, many of these technologies can be retrofitted into operating units.

Because the F frame accounts for a majority of current new unit sales, this infusion of technology yields significant savings in fuel and emissions. Figure 2 below shows the total impact of Siemens Westinghouse ATS technology on $CO_2$ emissions. Note that much of the net benefit is the result of Siemens Westinghouse's approach of expediting and expanding ATS technology through evolutionary introduction and infusion into mature frames.

## ATS TECHNOLOGY IN OPERATION

The W501G is the first major introduction of the ATS Technology. The W501G incorporates the following ATS engine features:

- ATS advanced 3D compressor
- Advanced brush seals and abradable coatings
- Closed-loop steam cooling
- High temperature bond and thermal barrier coatings
- ATS Row 4 turbine blade.

The first W501G was ignited in April 1999, at the City of Lakeland, Macintosh #5 site. The unit is undergoing extensive testing and verification. Commercial release is planned for the March 2000, and conversion to combined cycle is scheduled for 2001.

The test program includes over 3000 sensors and measured parameters. The test program consists of two phases – commissioning and emissions/performance mapping and thermal paint testing. For the emissions/performance mapping phase, testing will target combustion system variables and will provide engine performance mapping for different operating conditions such as IGV position and exhaust temperature. Following the initial testing, the engine will be opened up and selected instrumented components will be removed. Turbine flowpath components with varying cooling designs and combustion components, which have been prepared with thermal paint, will be installed. To react the thermal paint, the engine will be brought up to full load held for approximately five minutes and then shutdown. This will set a signature pattern in the thermally-sensitive painted surfaces to provide a . After the paint is reacted, the thermal paint parts will be removed and interpreted providing a mapping of the entire surface of part. This allows better understanding and potential optimization of the cooling flow. After the thermal paint test, the unit will be inspected with selected parts removed for examination.

**ATS Advanced 3D Compressor**

The W501G incorporates the first sixteen stages of the 27:1 nineteen-stage ATS Compressor with slight modification of the last three stages, and with the change of vanes 1 and 2 from modulated to fixed. As a result, the W501G operates at the ATS mass flow of 1200 lbs./sec, but at a pressure ratio of only 19:1 -- optimized for the G cycle.

The design is based on three-dimensional inviscid flow analyses and on custom-designed, controlled-diffusion airfoil shapes. Controlled-diffusion airfoil design technology is an improvement evolved from the aircraft engine industry, where this concept has been applied successfully over many years. The mechanical integrity of each stationary and rotating airfoil was verified by finite element analyses. The airfoil designs satisfied steady stress and endurance strength criteria. Each airfoil was tuned to avoid potentially harmful resonant frequencies.

To verify the aerodynamic performance and mechanical integrity of the new high pressure ratio design, the full-scale W501ATS compressor was manufactured and tested in 1997 at a specially-designed facility at the U.S. Navy Base in Philadelphia. To reduce the required power to the 25 MW available at the test facility, the compressor test was carried out at subatmospheric inlet conditions.

The compressor was instrumented with static pressure taps, fixed temperature and pressure rakes, thermocouples, tip clearance probes, blade vibration monitoring probes, rotor vibration probes, acoustic probes, and strain gauges. Provisions were made for radial traverses in eight axial locations in the compressor and in four radial locations in the inlet duct. A dedicated data acquisition system collected and reduced the test data from more than 500 individual measurements. Computer screens displayed important performance and health monitoring parameters in real time. After commissioning of the compressor test facility, an extensive test program examined the mechanical and aerodynamic performance. The test program included design point performance verification, blade vibration, diaphragm strain gauge measurements, inlet guide vane and variable stator optimization, compressor map definition, and starting characteristics optimization. The compressor testing was successfully completed ahead of schedule, and all mechanical and aerodynamic performance expectations were confirmed.

The ATS-developed compressor technology has also been retrofitted into the W501F product line. Using the analytical techniques developed and proven in the ATS program, the W501F compressor was upgraded in the latest improvement to this successful frame. This advanced compressor is being offered on new W501F units. In addition, the redesigned compressor can be retrofitted to any of the fleet of 42 W501Fs sold or in operation. Applying this ATS technology to the W501F expands the benefit of the ATS program, because the W501F compromises more the 70% of future units that are sold or on order at Siemens Westinghouse.

## Brush Seals and Abradable Coatings

To minimize air leakage, as well as hot gas ingestion into turbine disc cavities, brush seals were incorporated into the W501ATS engine design at several locations: under the compressor diaphragms, at the turbine disc front, under turbine rims, and at the turbine interstages. Tests were carried out on test rigs for the different brush seal locations to develop effective, rugged, reliable, and long life brush seal systems. At the Philadelphia U.S. Navy Base, full-scale brush seals were tested as part of the ATS Compressor test, which verified the brush seal low leakage and wear characteristics.

To date, ATS-developed brush seals have been successfully incorporated and operated in W501G and later W501F product lines. Pre- and post-upgrade tests have demonstrated performance improvement in retrofit applications.

Considerable performance benefits can be obtained by reducing compressor and turbine blade tip clearances. Abradable coatings permit tip clearances to be minimized without fear of damaging hardware, and they provide more uniform tip clearances circumferentially. Abradable coatings, identified for compressor and turbine applications, were tested to determine abradability, tip-to-seal wear rate, and erosion characteristics. These ATS-developed abradable coatings have been incorporated into the W501F and W501G compressor and front turbine stages (1 and 2). The later turbine stages (3 and 4) employ shrouded blades with honeycomb seals.

## Closed-Loop Steam Cooling

Using closed-loop steam cooling on transitions and turbine stationary components has two advantages. First, more compressor delivery air is available for premixing with the fuel gas in the combustor hot end. This allows very lean premixed combustion and makes possible the restriction of NOx emissions to single digits. Second, closed-loop steam cooling significantly improves cycle efficiency by reducing the amount of chargeable air used for cooling and sealing.

The ATS transitions, which duct the hot combustor exit gases to the turbine inlet, are closed-loop steam cooled with air as an alternate coolant. Steam enters the engine through four external connections and is routed to each transition supply manifold through internal piping. The supply manifold feeds the steam to an internal wall cooling circuit. After cooling the transition walls, the steam is collected in an exhaust manifold and ducted out of the engine. The W501G employs the ATS transition. The testing at Lakeland has confirmed the ability to switch between steam and alternate air cooling. As anticipated, actual measured metal temperatures proved to be lower in the new closed-loop steam cooled design than in existing open-loop air-cooled design.

## High-Temperature Thermal Barrier Coatings

Thermal barrier coatings are an integral part of the W501ATS engine design. A development program is in progress to develop an advanced bond coat/TBC system with a projected service life of more than 24,000 hours. Different bond coats and ceramic materials were evaluated under accelerated oxidation test conditions and down selected. An advanced bond coat/TBC system mechanical integrity and durability was demonstrated in more than 24,000 hours of cyclic testing at 1010°C (1850°F). This advanced bond/coat TBC system has been incorporated on the W501G Row 1 and 2 blades. This coating will improve both the life and durability of these parts, and it can potentially improve future engine performance by reducing the amount of cooling air required.

### ATS Row 4 Turbine Blade

The 25% increase in engine mass flow, compared with the baseline F class machines, necessitated an advanced design Row 4 turbine blade to avoid increasing turbine exhaust losses. The ATS Row 4 blade is an uncooled, interlocked, Z-shrouded, cast airfoil. Because the W501G employs the ATS compressor and associated massflow, this blade was first introduced on the W501G. At the Lakeland site test the blade is instrumented with vibration monitors and strain gauge telemetry. In testing to date the blade has performed as predicted in both aerodynamic performance and mechanical strength.

## DEVELOPMENT ACTIVITIES

### Steam-Cooled Vane

Development activities are focused on extending the W501G frame to ATS efficiencies through the introduction of additional technology advancements. The next major step will be the addition of a thin-walled, closed-loop, steam-cooled Row 1 turbine vane to the W501G. The steam-cooled vane will extend the benefits of the steam-cooled transition by eliminating cooling air from the Row 1 vane. The result will be a combination of increased rotor inlet temperature and decreased burner outlet temperature. The benefit will be improved efficiency and reduced NOx.

The ATS steam cooled vane will be first tested in an engine sector rig. The test rig, located at Arnold Engineering Development Center at the Arnold Air Force Base in Tennessee, consists of a full-scale combustor basket and transition and a $1/16^{th}$-sector vessel, which will operate up to full ATS pressures and temperatures. The vane will be instrumented to verify analytical predictions of metal temperatures, heat transfer coefficients, and stress.

After validation in the $1/16^{th}$-sector rig, the vane will be retrofitted into a W501G. A comprehensive test program will verify satisfactory vane performance and improved plant performance. Test parameters will include vane metal temperature, stress, and steam temperatures.

### Catalytic Combustion

Achieving ultra-low NOx emissions at the ATS firing temperature required a considerable development effort, balancing the design for efficiency, emissions, mechanical integrity, and cost. Through a development program with Precision Combustion, Inc. (PCI), Siemens Westinghouse is developing catalytic combustion for its ATS engine and extended fleet. Catalytic combustion will ensure that the ATS emissions objectives are met across a wide operating range. Activities to date consisted of catalyst selection, pilot design, and component testing. Long term catalyst testing has already been completed, and has verified that the SWPC/PCI design catalytic combustor can operate successfully without a pre-burner.

### Materials

W501ATS operating conditions extend the technology envelope of current materials; hence, materials development work is an important element in the evolution and success of the W501ATS engine. Development programs have been carried out on effect of steam cooling on materials, blade life prediction, advanced vane alloy, directionally solidified blade alloy properties, single crystal material data, and single crystal airfoil casting. To achieve W501ATS program performance and mechanical integrity goals, single crystal vanes and blades are used in the W501ATS engine. Casting development programs have been conducted to demonstrate castability of large industrial turbine airfoils in CMSX-4 alloy. Casting trials on first stage vanes and blades that incorporate thin-wall cooling-design features demonstrated the viability of this concept. However, further work is required to improve yield and associated cost. Attention is being focused on alternative manufacturing methods and alloys to improve the part cost.

**Coatings**

Novel ceramic chemistries were investigated in an effort to improve upon the phase stability and sintering resistance of 8% yttria-stabilized-zirconia TBC. Under a related program, DOE-Oak Ridge National Laboratory Thermal Barrier Coatings Program, new ceramic TBCs have been identified with superior performance. With the selection of a new bond coat, identified earlier in the program, and a new TBC composition, a TBC system is available for application at estimated ATS surface temperatures.

An advanced abradable TBC system was developed under the ATS program. The system is designed for the ATS Row 1 turbine ring segment, which forms the outer flow path surface around the Row 1 turbine blade. In this application, the system requires state-of-the-art thermal barrier properties and sufficient abradability. Laboratory component testing verified its ability to withstand high surface temperatures, large thermal gradients, and engine-typical blade incursion. To verify performance in an operating engine, seven Row 1 turbine ring segments were installed in an engine in October 1998. These segments were inspected with excellent results in June of 1999, after 6000 hours of operation. No detectable erosion or blade tip wear was observed.

## SUMMARY

Technology development efforts have demonstrated that ATS Program goals are obtainable. The results of the technology development programs were incorporated into the W501ATS design. Based on input from customers, Siemens Westinghouse is pursuing an evolutionary introduction of ATS technology. The W501G, the first step in this evolution, introduces several ATS technologies such as closed-loop steam cooling, advanced compressor design, and high temperature materials. The first W501G is in commissioning at Lakeland, FL, with commercial release schedule for March 2000. In addition, Siemens Westinghouse is infusing ATS technologies into its entire product line. This approach will result in a lower-risk ATS engine and will significantly increase the net benefits of the program.


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