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STATUS OF WESTINGHOUSE'S ADVANCED TURBINE SYSTEMS PROGRAM

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ABSTRACT

This paper describes the status of Westinghouse's Advanced Turbine Systems (ATS) Program. This program was undertaken in response to U.S. Department of Energy, Office of Fossil Energy requirements for greater than 60% net plant thermal efficiency, less than 10 parts per million NOx emissions, 10% reduction in the cost of electricity and state-of-the-art Reliability-Availability-Maintainability (RAM) levels (Ali and Zeh, 1996). An extensive four-year program was undertaken to develop the required technologies and design an advanced gas turbine. The gas turbine design and most of the technology verification programs have been completed. The 501ATS engine employed innovative aerodynamic, combustor, cooling, sealing, and mechanical designs, as well as advanced materials, coatings, and casting technologies to achieve the program goals. The incorporation of the 501ATS gas turbine in a world-class combined cycle plant will result in more than 420 MW net output power and greater than 60% net LHV based plant thermal efficiency.

INTRODUCTION

The 501ATS program is an ambitious multi-year effort to develop the necessary technologies, which will result in a significant increase in natural gas-fired power generation plant efficiency, a decrease in cost of electricity and a decrease in harmful emissions. In Phase 1 of the ATS Program, preliminary investigations on different gas turbine cycles demonstrated that net plant efficiency greater than 60% could be achieved (Little et al., 1993). The more promising cycles were evaluated in greater detail in Phase 2 and the closed-loop cooled combined cycle was selected because it offered the best solution with the least risk for achieving the ATS Program goals of net plant efficiency, emissions, cost of electricity, RAM, as well as commercial operation by the year 2000 (Briesch et al., 1994).

The Westinghouse ATS plant was based on an enhanced technology gas turbine design combined with an advanced steam turbine and a high efficiency generator. The achievement of ATS program goals required advancements in a broad range of technologies, such as aerodynamics, combustion, sealing, cooling, coatings, and materials (Bannister et al., 1995; Diakunchak et al., 1996). To attain the RAM targets, the utilization of proven design features was required, with quantified risk analysis, and advanced materials, coatings, and cooling technologies.

The 501ATS engine is the next frame in the series of successful utility turbines developed by Westinghouse over the last 50 years (Scalzo et al., 1994). During that time, Westinghouse engineers made significant contributions in advancing gas turbine technology as applied to heavy-duty industrial and utility engines. Some of the innovations included single-shaft, two-bearing engine design, cold-end drive, axial exhaust, first cooled turbine airfoils in an industrial engine, and tilting pad bearings, features which all major gas turbine manufacturers have incorporated in their designs. The evolution of large gas turbines started at Westinghouse with the introduction of the 45 MW 501A

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engine in 1968 (see Figure 1). Continuous enhancements in performance were made up to the 100 MW 501D5 introduced in 1981. The next engine was the 160 MW 501F, introduced in 1991 (Scalzo etal., 1988). The 230 MW 501G was next in the series and is the initial step in 501ATS engine development (Southall and McQuiggan, 1995). Each successive engine design was based on the proven concepts used in the previous design.

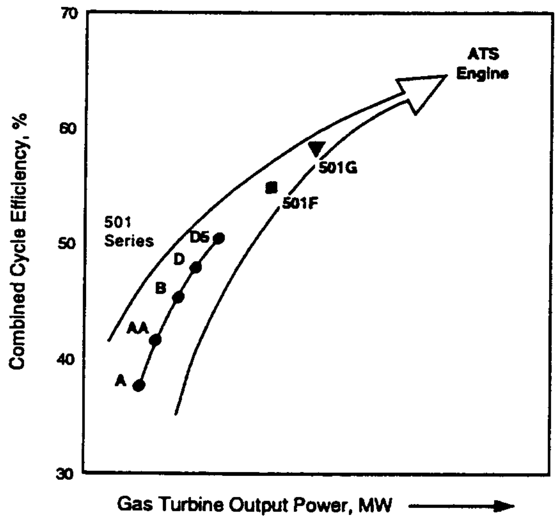

Figure 1. Evolution of Large Westinghouse Gas Turbines

Westinghouse's strategy to achieve, and exceed, the ATS Program goals was to build on the proven technologies used in the successfully operating fleet of its utility gas turbines, such as the 501F, and to extend the technologies developed for the 501G.

ATS DESCRIPTION

The Westinghouse ATS plant power train consists of the gas turbine, generator, and steam turbine, connected together in an in-line arrangement with a self-shifting and synchronizing clutch located between the generator and the steam turbine (see Figure 2). The ATS plant conceptual design is based upon the Westinghouse Reference Plant design practice. The design incorporates flexible proven features that minimize design changes usually required for customizing the plant to local conditions. The gas turbine exhaust passes through the three-pressure level heat recovery steam generator (HRSG) before being exhausted through the stack. The HRSG incorporates additional features to recover rotor cooling air heat and to preheat the fuel. The high pressure steam turbine exhaust steam is used to cool the transitions and the first two stages of stationary vanes. The reheated steam is then returned to the steam cycle for

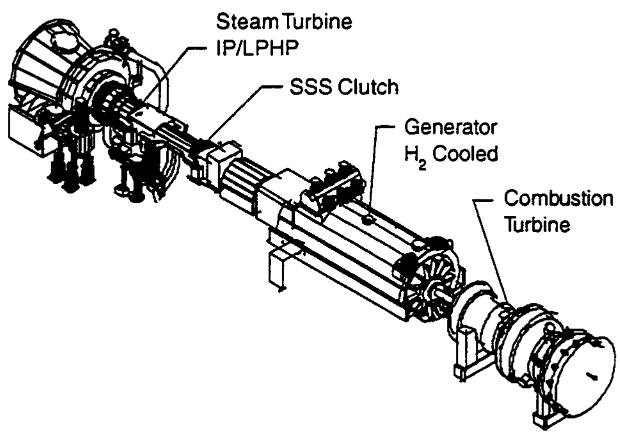

Figure 2. ATS Single Shaft Power Train

induction into the intermediate pressure steam turbine. The two case axial exhaust reheat steam turbine employs advanced aerodynamic design methods. High performance 3-D bowed impulse and reaction blades are used on the high pressure and intermediate pressure turbines respectively. The low pressure turbine incorporates 42-inch (1.07 m) long Titanium blades on the last stage. The 60-Hz, two-pole generator is an extension of the Westinghouse hydrogen-cooled modular design concept.

The 501ATS engine (see Figure 3) is a state-of-the-art 300 MW class design incorporating many proven design features used in previous Westinghouse gas turbines as well as new design features and technologies required to achieve the ATS Program goals.

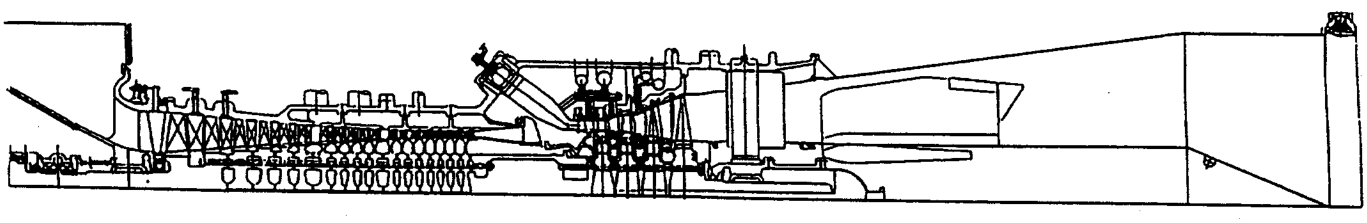

Figure 3. 501ATS Engine Cross-Section

Compressor

The ATS compressor (see Figure 4) shared many common parts with the 501G 16-stage compressor. The mass flow was identical to the 501G, but the 501ATS higher rotor inlet temperature and closed-loop cooling has required an increase in pressure ratio from 19:1 to 27:1. This increased pressure ratio was achieved by adding three stages

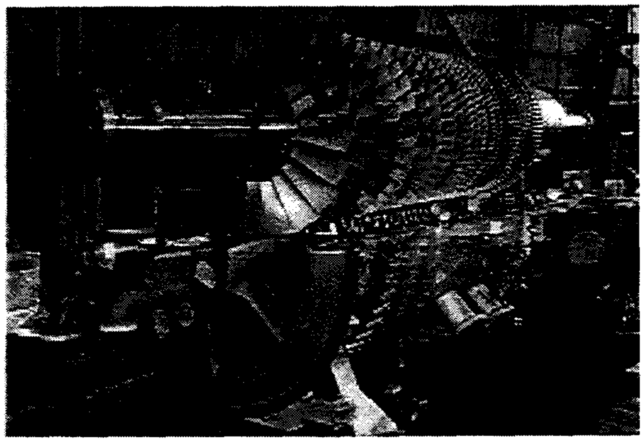

Figure 4. 501ATS Compressor

to the rear of the 501G compressor. The latest 3-D viscous codes and custom-designed airfoils were used in the compressor aerodynamic design. Variable stators have been added to stages 1 and 2 to improve starting capability and part-load performance.

Combustion System

The 501ATS incorporated 16 combustors based on the lean premixed multi-stage piloted ring design. The burner outlet temperature was kept at the same level as in the 501F and 501G, by using closed-loop steam cooling (with air as an alternate coolant) in the transitions and turbine stators, so that more compressor delivery air was available in the combustor head end (see Figure 5). Therefore, this allowed very lean, premixed combustion and hence single digit NOx emissions.

Turbine

The four-stage turbine design was based on 3-D design philosophy and viscous state-of-the-art analysis codes. The airfoil loadings were optimized to enhance aerodynamic performance while minimizing airfoil solidity. The reduced solidity resulted in lower cooling requirements and increased efficiency. To further enhance plant performance, the following features were included: turbine airfoil closed-loop cooling, active blade tip clearance control on the first two stages, improved rotor sealing, and optimum circumferential alignment of airfoils.

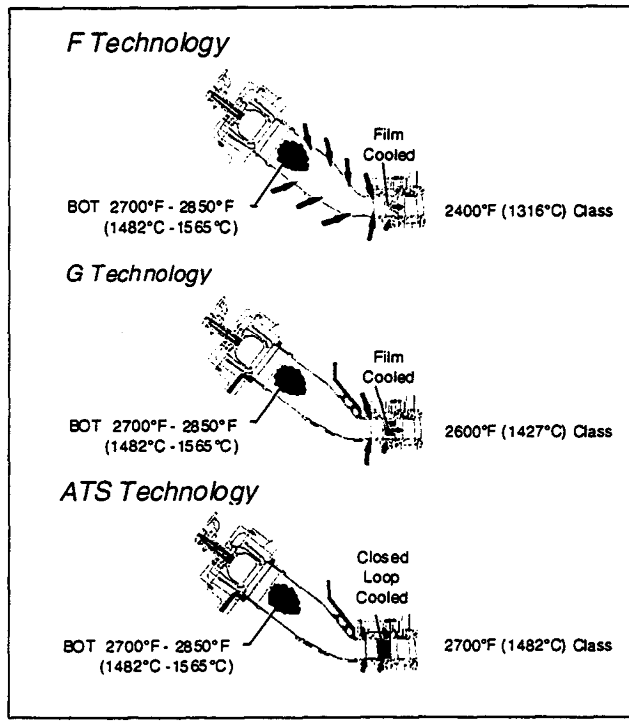

Figure 5. Closed Loop Cooling Technology

The 501ATS engine utilized advanced thin wall turbine airfoil designs with thermal barrier coatings and advanced aero engine cooling technology. Closed-loop steam cooling was used on the first and second stage vanes. Closed-loop air cooling was used on the first two stages of blades. Air was chosen for blade cooling to eliminate the risks of steam corrosion, deposition, and complexity that closed-loop cooling with steam poses. An added advantage with air cooling is that the air can be cooled after it is removed from the combustor shell so that only relatively small amounts of cooling air are required. The cooling air will be filtered to remove dirt particles before being ducted to the rotor blades. The difference in plant thermal efficiency between blade closed-loop cooling by air instead of steam was estimated to be about 0.2%. Thus, based on a cost benefit analysis and RAM analysis, closed-loop air cooling was chosen for the 501ATS turbine.

Westinghouse has been using thermal barrier coatings (TBC) on turbine airfoils since 1986 and has built an extensive experience base. It is a standard "bill of material" for new 501D5, 501F, and 251B11/12 engines. Recent field trials on TBC coated turbine airfoils have demonstrated excellent results after 24,000 operating hours. To achieve further improvements, the 501ATS turbine incorporated advanced coating systems comprised of new ceramic materials and improved bond coats.

The latest aero engine blade and vane nickel-based alloys were used in the 501ATS turbine design. To provide increased creep strength and fatigue resistance compared to conventional materials, single crystal nickel alloy, CMSX-4, was employed on the first stage vanes and blades.

Rotor Design

Due to the high power level transmitted through the rotor and the resulting high stresses, rotor design is an extremely important component of the engine. The 501ATS turbine rotor consisted of four ruggedized alloy steel discs clamped together with 12 through-bolts. Low cost alloy steel was used to extend the excellent past operating experience with this material to the ATS engine. In this design, torque transmission and alignment were achieved by the use of a Curvic™ clutch, which is a beveled male and female tooth form. This design has been proven by use on all Westinghouse-designed gas turbines over the past 40 years.

Extensive finite element analysis modeling was carried out during the rotor design process to calculate rotor critical speeds and cyclic life. To ensure rotor stability, a transient analysis from startup to baseload was carried out to verify that there was no slipping or gapping of the torque carrying members. The analysis has demonstrated that during all conditions analyzed, the torque carrying Curvic™ clutch arms do not come out of engagement, thus virtually eliminating frettage or slippage which could give rise to vibration or cracking.

The compressor rotor incorporated a series of discs clamped together with 12 through-bolts. The torque transmission was via friction and radial keys located between all discs. This method was also employed on the 501F with excellent reliability. In this design, disc alignment was maintained by a spigot at the base of the discs and by the shoulder on the radial pins. Computer modeling was used to ensure the rotor stability over its entire operating range with no possibility of slippage or gapping.

TECHNOLOGY VERIFICATION PROGRAMS

To ensure that ATS Program goals are achieved, an extensive technology verification program was conducted in the following areas: combustion, cooling, aerodynamics, leakage control, coatings, and materials.

Combustion

The piloted ring combustor was selected for the 501ATS engine as the most successful candidate of several dry low NOx combustors developed by Westinghouse over the last 10 years (see Figure 6). This combustor consists of a pilot and two axially staged premixed zones, the primary and secondary zones. Premixed fuel and air is introduced into the primary zone where the combustion is stabilized by a swirl-produced recirculation zone and a centrally located pilot. The secondary zone, located downstream of the primary zone, is supplied with premixed fuel and air through an annular duct surrounding the primary zone. The piloted ring combustor has achieved single digit NOx emissions and excellent stability on low pressure tests. It is currently undergoing high pressure testing to optimize emissions and expand the operating range by improving fuel and air mixing in the primary premixing passage.

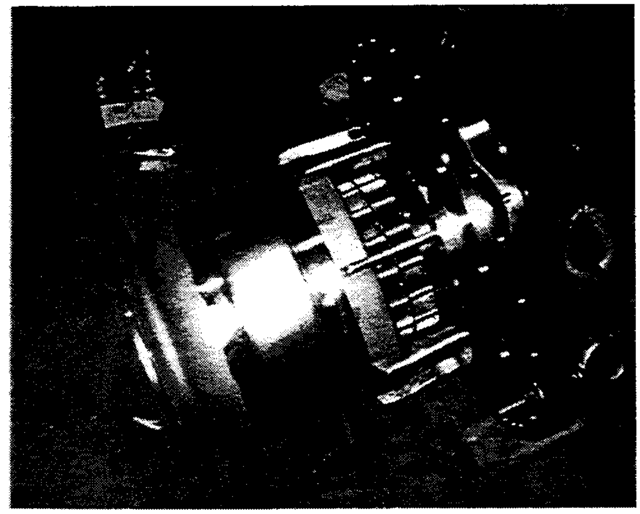

Figure 6. 501ATS Piloted Ring Combustor

Cooling

Closed-loop turbine airfoil cooling contributes significantly to increase in plant performance by eliminating cooling air injection into the turbine gas path. This results in increased gas energy level during the expansion process, by raising the gas temperature downstream of the first stage vane, and mixing loss elimination due to the cooling air ejection. An additional benefit resulting from closed-loop cooling is a reduction in NOx emissions because more air is available for the lean premix combustion while maintaining the same burner outlet temperature. The absence of a cooling air film to shield the flow path surfaces from the hot gases and no trailing edge cooling air ejection to enhance cooling in the critical trailing edge region presents a challenge to a successful closed-loop cooling design. This challenge was overcome in the 501ATS turbine thin wall airfoil design by utilizing the following: (1) airfoil aerodynamic design tailored to provide minimum gas side heat transfer coefficients, (2) minimum coolant inlet temperature, (3) thermal barrier coating applied on airfoil and end wall surfaces to reduce heat input, (4) maximized internal surface area, (5) turbulators to enhance internal heat transfer coefficients, and (6) minimum outside wall

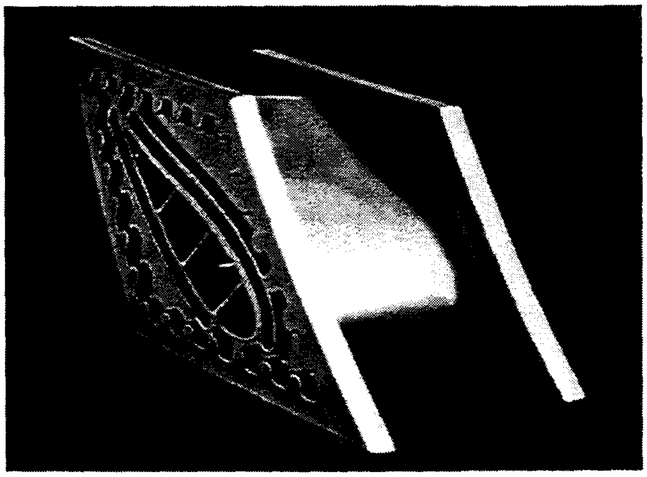

Figure 7. First Stage Vane

thicknesses to reduce wall temperature gradients and hence the internal heat transfer coefficients required to cool the airfoil.

The thin-wall closed-loop cooled first stage vane and blade design was completed and casting development is progressing at Allison-Single Crystal Operations Division of Rolls Royce (see Figure 7). To verify the critical cooling designs, a comprehensive three-part program was undertaken. The internal heat transfer coefficients and pressure drops were measured on seven plastic models of the different vane and blade cooling features at Carnegie Mellon University. A liquid crystal thermochromic paint technique was used to measure the internal heat transfer coefficients. Test results confirmed the analytical predictions. The outside heat transfer coefficients will be measured on model turbine tests. The first stage vane cooling design will be verified at ATS operating conditions in a hot cascade test rig.

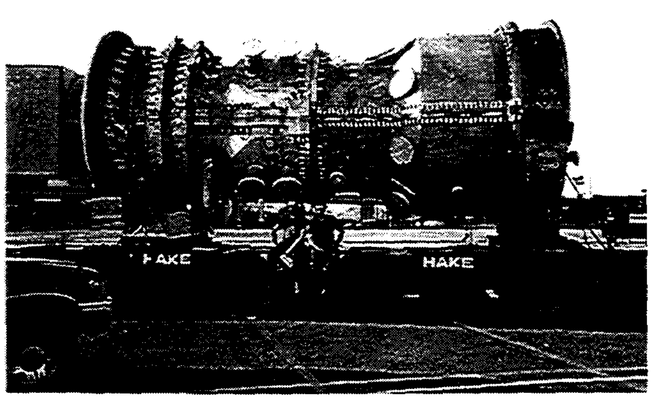

Figure 8. 501ATS Test Compressor Assembly

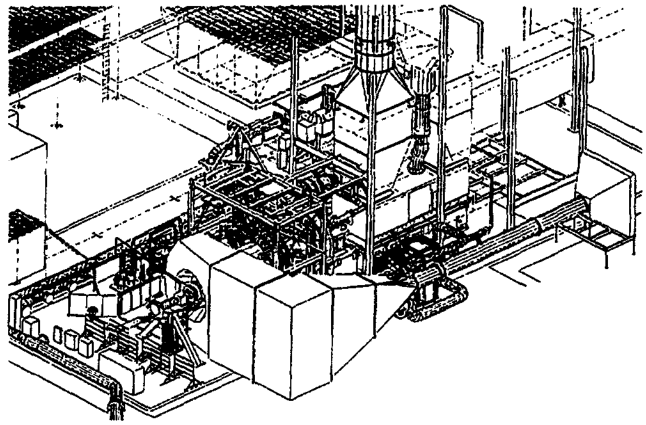

Figure 9. 501ATS Compressor Test Facility Schematic

Compressor Aerodynamics Development

The full-scale 501ATS compressor (see Figure 8) verification tests were carried out successfully in a specially designed facility erected at the U.S. Navy Base in Philadelphia. To reduce the compressor power requirement

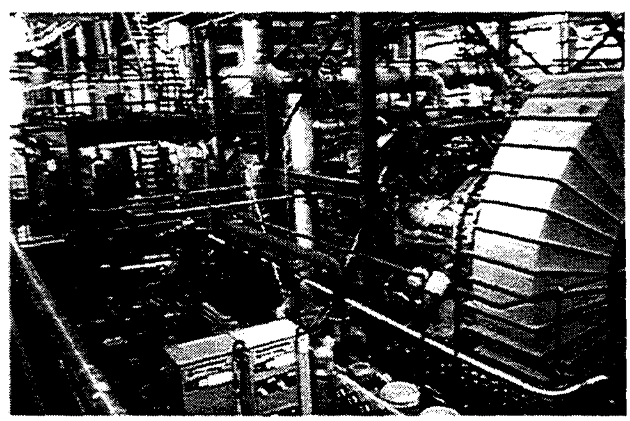

Figure 10. 501ATS Compressor Test Facility

to the level available at the site, the facility was designed for subatmospheric inlet pressure (see Figures 9 and 10). The inlet system consisted of a filter house, straight pipe with a flow straightener and a flow meter, inlet throttle valve, diffuser with flow straightening devices, 90° bend with turning vanes, and a silencer. Because of the subatmospheric operation, two stages of compressor bleed air were ducted into the inlet diffuser, after passing through coolers. The exhaust system included a large diameter back pressure valve to provide control on the test pressure ratio. A small diameter quick-acting valve, located in a bypass line around the large back pressure valve, was used for recovery from compressor surge.

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 four radial locations in the inlet duct. More than 500 individual measurements were recorded. A dedicated data acquisition system was used to collect and reduce the test data. Important performance and health monitoring parameters were displayed on computer screens in real time. After the compressor test facility was commissioned, an extensive test program was performed. The test program included design point performance verification, blade vibration and 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. All mechanical and aerodynamic performance expectations were confirmed. Since the front stages of the 501ATS compressor are the same in the 501G, this test was also a confirmation of the 501G compressor mechanical integrity and performance.

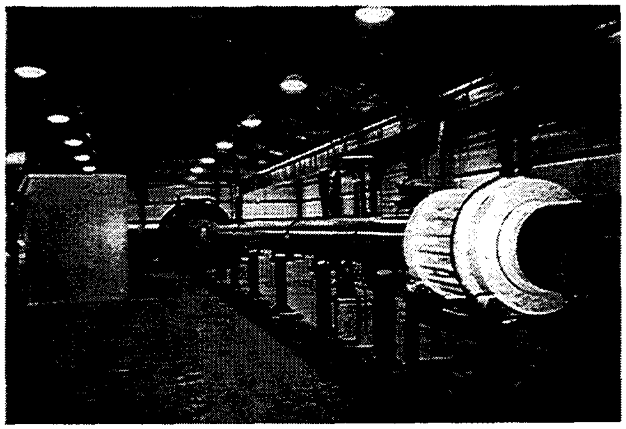

Figure 11. Model Turbine Test Facility

Turbine Aerodynamic Development

A program was put in place to test a 1/3-scale model of the first two 501ATS turbine stages in a test rig located at Ohio State University (see Figure 11). This is a shock tube test facility, which operates as described below. The shock tube is pressurized, the test chamber is evacuated, exit traverse is spun up to speed, and the turbine rotor is accelerated to speed by an air drive. A diaphragm is exploded and the shock tube discharges, resulting in a shock at the test section inlet. The turbine is accelerated to the desired test speed, exit area chokes, and the turbine reaches stable design speed, pressure ratio and mass flow. The test data is then recorded in a fraction of a second. The program objectives were: to verify aerodynamic performance with reduced airfoil solidity, to quantify performance benefits due to optimum circumferential alignment of turbine airfoils, and to measure outside heat transfer coefficients on the airfoils of this advanced 3-D aero design turbine. The model turbine component manufacture was completed. Pressure sensor, heat flux gauge, and thermocouple installation on the model turbine airfoils was completed. The testing will start at the beginning of 1998.

Leakage Control

To reduce air leakage, as well as hot gas ingestion into turbine disc cavities, brush seals were incorporated under the compressor diaphragms, turbine disc front, turbine rim, and turbine interstage locations (see Figure 12). A development program was initiated to incorporate an effective, reliable, and long-lasting brush seal system into a heavy-duty industrial gas turbine (Chupp et al., 1997). Tests were performed to select the appropriate bristle materials, to quantify wear characteristics and to determine leakage. The brush seal performance under the compressor diaphragms was verified during the 501ATS compressor testing. To test their performance over long operating times, turbine interstage brush seals were installed on a new 501F engine and will be retrofitted into 501D5 engines.

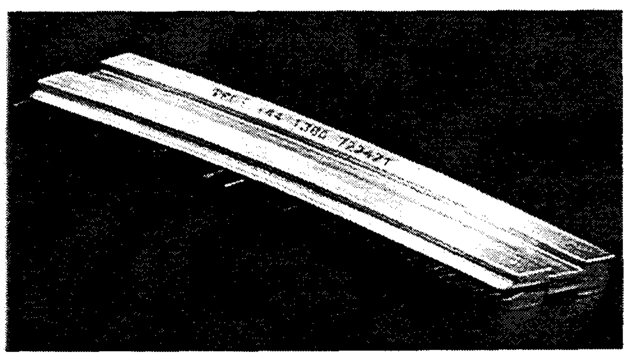

Figure 12. Brush Seal Segment

A face seal was designed to prevent rotor cooling air leakage as it is introduced at the rotor rear. Seal hardware has been ordered and a test rig is being constructed. Tests will be carried out to verify the face seal performance.

Coatings

Long service life turbine component coating systems are essential to the success of the 501ATS engine. To ensure this, a program is in progress to develop an improved bond coat/TBC system capable of operation for more than 24,000 service hours. Coatings designed for improved manufacturing throughput are being developed. Different bond coats are being evaluated under accelerated oxidation test conditions. New ceramic candidate materials are also undergoing testing. The objective of this program is to combine the optimum bond coat with the best performing TBC to provide a coating system with maximum service life at the ATS operating conditions. An advanced bond coat/TBC system has accumulated more than 20,000 hours in cyclic testing at 1010°C (1850°F) with excellent results (see Figure 13).

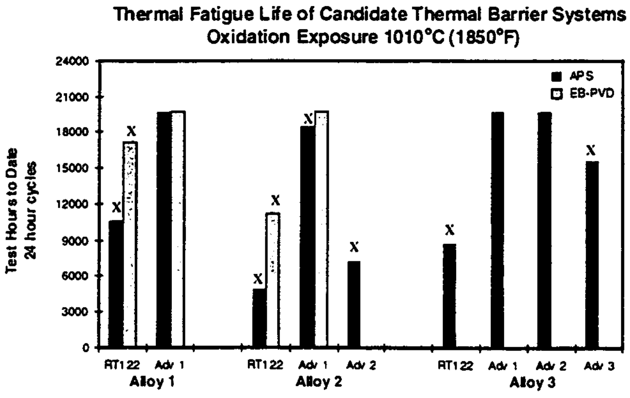

Figure 13. Advanced TBC Systems Test Results

Materials

To enhance performance and reliability, single crystal (SC) blades are used in the ATS engine. A casting development program was carried out to demonstrate castability of large industrial turbine blades in CMSX-4 material. Existing 501F engine tooling was used to cast single crystal blades. The castings were evaluated by grain etching, selected NDE methods and dimensional inspection methods to determine their metallurgical acceptability. After several trials, excellent results were obtained on a solid and a cored blade thus demonstrating that SC blades are castable in CMSX-4 alloy. Further process development is in progress to optimize post-cast heat treatment, evaluate effects of grain defects, generate SC material design data, and further develop the casting process for large industrial turbine blades.

SUMMARY

Technology development efforts to date have demonstrated that ATS Program goals are obtainable. The results have been incorporated into the 501ATS design. Full-scale tests on the 501ATS compressor verified its mechanical integrity and aerodynamic performance. High pressure testing on the ATS piloted ring combustor will be carried out to optimize the design and demonstrate single digit NOx emissions. The two-stage model turbine tests, to verify aerodynamic performance and to measure outside heat transfer coefficients, will be completed at the beginning of 1998. Rig testing will be completed on the turbine brush seals and rotor face seal. Pre-production casting development will continue on the single crystal thin wall stage 1 vanes and blades and thick wall stage 2 blades. Long term verification tests on advanced bond coat/TBC system will continue on test rigs and rainbow tests with coated blades on operating engines to verify the advanced bond coat/TBC coating system.

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