**Advanced Turbine Systems Program
Conceptual Design and Product Development**

**Annual Report
August 1994 - July 1995**

October 1994

Work Performed Under Contract No.: DE-AC21-93MC30247

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Westinghouse Electric Corporation
Orlando, Florida

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ADVANCED TURBINE SYSTEMS PROGRAM
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INTRODUCTION

The objective of the ATS Program is to develop ultra-high efficiency, environmentally-superior, and cost-competitive gas turbine systems for base-load application in utility, independent power producer, and industrial markets. The following specific performance targets have been set using natural gas as the primary fuel for the large-scale utility systems:

- Greater than 60% plant cycle efficiency (on LHV basis)
- NOx emissions 10% lower than current values
- Cost of electricity 10% less than current values
- RAM as for current combined cycle plants
- Demonstration by year 2000

The ATS engine will be the next model in the series of large heavy-duty gas turbines developed by Westinghouse. Westinghouse has been involved in gas turbine design and development since 1945. During that time, Westinghouse engineers made significant contributions in advancing gas turbine technology, especially in the field of heavy-duty engines used in industrial and electrical utility applications. Some of the innovations included single-shaft two bearing design, cold end-drive, axial exhaust, cooled turbine airfoils in an industrial engine, and tilting pad bearings. The improvement in turbine performance and mechanical efficiency have been continuous and evolutionary. The Westinghouse 501G is a technological extension of the 501F, and the ATS gas turbine is evolving from the technological advances being made in the 501G.

This report discusses the major accomplishments achieved during the second year of the ATS Phase 2 program.

PROJECT OVERVIEW

The Westinghouse ATS Phase 2 Program has been defined with eight major tasks:

- Task 1.0 Management Plan
- Task 2.0 National Environmental Policy Act (NEPA) Information
- Task 3.0 Selection of Natural Gas-Fired Advanced Turbine System (GFATS)
- Task 4.0 Conversion of a Gas-Fired Advanced Turbine System to a Coal-Fueled Advanced Turbine System (CFATS).
- Task 5.0 Market Study
- Task 6.0 System Definition and Analysis
- Task 7.0 Integrated Program Plan
- Task 8.0 Design and Test of Critical Components

The status of these major tasks and the work accomplished during the past year (August 1994 through July 1995) are described in the following sections of this report.

1.0 PROJECT PLAN

The original Management Plan was updated to reflect the changes made to the contract with the addition of Tasks 8.10 through 8.18. A second contract modification was made during the second quarter 1995 adding Tasks 8.19 through 8.38. An additional change to the Management Plan is being made to reflect these changes to the Phase 2 scope-of-work.

2.0 NATIONAL ENVIRONMENTAL POLICY ACT (NEPA) INFORMATION

Since the submittal of the Topical Report for NEPA Information, dated November 19, 1993, two additional metallurgical test sites were surveyed for compliance with NEPA requirements and found to have no additional environmental impacts.

The Clemson University Environmental Health and Safety Report required by NEPA was completed and approved by METC.

The NEPA information for Phase 2 is complete.

3.0 SELECTION OF NATURAL GAS-FIRED ADVANCED TURBINE SYSTEMS (GFATS)

A review of unconventional steam turbine configurations for combined cycle applications was carried out. The results indicated that there is a potential for improving the steam turbine efficiency, and hence the ATS combined cycle efficiency.

The final Topical Report on "Selection of Natural Gas-Fired Advanced Turbine System" was issued in December, 1994.

This task is now complete.

4.0 SELECTION OF COAL-FIRED ADVANCED TURBINE SYSTEMS (CFATS)

This task was completed during the first year of Phase 2.

5.0 MARKET STUDY

The analytical computer software required to perform a competitive economic analysis was obtained. The analysis used a screening approach against selected alternative technologies. Factors were chosen to evaluate the levelized cost of electricity as a

function of capacity factor. The effort showed how the ATS will perform competitively in peaking, intermediate and baseload applications.

The initial market study results reported by our consultant, Arthur D. Little, were reviewed in July and the final report will be completed in November 1995. The objective of the study was to provide a forecast of the worldwide potential for the ATS gas turbine technology in the time period 2000 to 2014.

6.0 SYSTEM DEFINITION AND ANALYSIS

ATS engine and plant conceptual design reviews were held on July 26, 1995. Presentations on engine design were made by engineers who worked on the different engine components. Gilbert/Commonwealth, Inc. (our architect, engineering consultant) described the ATS plant design. There were no major issues raised with either the engine or the plant designs. However, the reviewers identified several action items and recommendations to enhance the ATS engine design and suggested future tradeoff studies to optimize the plant design.

A conceptual design was carried out to define the ATS engine. To provide high mechanical integrity and reliability, the ATS design incorporates proven design features used in previous Westinghouse gas turbines. These features include two-bearing rotor design, cold end-drive axial exhaust, individual combustors, four-stage turbine, single segment first stage turbine vanes and torque transmittal through curvic clutches between turbine disks. To achieve the ATS program performance and emissions goals necessitated the introduction of several new design features, such as closed-loop steam cooling, catalytic combustion components, advanced turbine blade coatings systems, advanced 3-D aerodynamic design, active blade tip clearance control and advanced sealing.

The ATS engine is an advanced 300 MW class design. The compressor design philosophy is based on that used in the advanced 501G compressor, but with additional enhancements. The aerodynamic design uses 3-D viscous codes, controlled diffusion airfoils and reduced airfoil thicknesses. To reduce under the stator air leakage, advanced sealing design is employed. Variable stators are incorporated in the front stages to improve starting and part-load operation.

The combustion system has 16-can annular combustors of lean-premixed multistage design with catalytic components. To limit NO_x emissions to 8 ppmv, nearly all the compressor delivery air must be premixed with the fuel. Closed-loop steam cooling is used, therefore, to cool the combustors and transitions. Steam is supplied and extracted through manifolds on the turbine blade ring.

The four-stage turbine is an extension of the advanced 501G turbine design. The 501G turbine efficiency was increased over that of the 501F by applying 3-D design philosophy and advanced viscous analysis codes. The airfoil loadings were optimized to enhance

airfoil efficiency while minimizing airfoil solidity. The increased loading resulted in reduced cooling requirements and enhanced engine efficiency. The following features are included in the ATS design: closed-loop cooling of vanes and blades; active blade tip clearance control to reduce tip clearance; and, improved rotor sealing.

To enhance ATS plant efficiency, closed-loop cooling is employed in the design of the turbine airfoils. The major benefit of closed-loop cooling is the elimination of cooling air ejection into the flow path. This results in an increase in gas temperature downstream of the first stage vane and hence an increase in gas energy level during the expansion process. A secondary benefit is the elimination of mixing losses associated with cooling air ejection. The combination of the above effects will result in a significant increase in ATS plant efficiency. In addition, the NO_x emissions will decrease because more air will be available for the lean-premix combustor at the same burner outlet temperature. Achieving acceptable blade metal temperatures in a closed-loop cooling design will be a challenge because of the absence of the cooling air film to shield the turbine airfoil and shroud walls and no shower-head ejection to provide enhanced cooling in the critical blade and vane regions. To produce optimized closed-loop cooling design the following approaches are utilized: 1) airfoil aerodynamic design tailored to give minimum gas side heat transfer coefficients, 2) minimum coolant temperature, 3) thermal barrier coating applied on airfoil and end wall surfaces to reduce heat input, 4) maximized cold side surface area, 5) turbulators used to enhance cold side heat transfer coefficients, and 6) minimum outside wall thicknesses to reduce wall temperature gradients, and hence, the internal heat transfer coefficients that would be required to cool the airfoil.

Preliminary investigation was carried out on the following turbine airfoil closed-loop cooling concepts: The thin wall shell/spar, thin wall casing and peripheral spanwise cooling hole. The thin wall shell/spar was selected as the prime candidate for the ATS cooling design. It achieves the desired qualities of thin walls and favorable cold-to-hot surface area ratio. This concept consists of a central airfoil shaped structure, the spar, around which a thin superalloy sheet, the shell, is diffusion bonded. There are small chordwise grooves on the spar outside surface. The spar has three cavities: the front and rear cavities supply the steam, and the mid cavity discharges the spent steam. Cooling channels extend in chordwise direction from a supply cavity to the discharge cavity. Holes drilled through the spar connect the cooling channels with the cavities. The trailing edge is cooled by spanwise holes.

The turbine rotor is constructed from a series of individual discs, spacer discs and a stub shaft. The turbine discs are of conventional design, except for a rotor bore used to supply the coolant.

The ATS engine has an axial exhaust diffuser similar to that used in previous Westinghouse designs. It consists of the exhaust cylinder and an exhaust manifold. The exhaust cylinder carries the hot end journal bearing. The tailcone is supported by tangential struts.

The basic configuration of the ATS plant is similar to that of the 501F Reference Plant. The power trains of both plants include one gas turbine and one multi-pressure steam turbine connected by a single shaft to a common generator. Both plants are fueled by natural gas and utilize mechanical draft cooling towers. The ATS plant generates considerably more power at a higher efficiency than the 501F plant, mainly because of the increased power and efficiency of the gas turbine and the higher throttle and reheat temperatures of the steam turbine.

The gas turbine of the ATS plant is larger and more efficient than the 501F because of its higher mass flow, firing temperature, and pressure ratio. The gas fuel is preheated using recovered low-grade heat from the HRSG, and the vanes and blades are closed-loop cooled.

The HRSG for both the ATS and 501F plant are triple pressure with vacuum deaeration. The thermal duty of the ATS plant is approximately 35 percent larger than the thermal duty of the 501F Reference Plant due to an increased flue gas flow and higher inlet temperatures.

The steam turbine cycle for the ATS plant is a single reheat cycle with higher throttle pressure, throttle temperature, and reheat temperature than the steam cycle in the 501F Reference Plant. The higher steam turbine exhaust flow of the ATS plant necessitates a double-flow LP exhaust. Changing from an axial-flow steam turbine exhaust to double-flow exhaust, as well as the 35 percent increase in thermal duty of the condenser, required a change in condenser configuration. For design convenience, a side entry "saddlebag" condenser was modeled rather than a vertical type. A comprehensive trade-off analysis will be performed to determine which condenser is more economically feasible.

All the mechanical, electrical, control, and chemical design criteria for the ATS plant conceptual design have been developed along with plant site and equipment arrangement drawings. In addition, a comprehensive plant equipment list and motor list have been developed.

7.0 INTEGRATED PROGRAM PLAN

The integrated program plan has been completed and is included in the Management Plan. The plan now includes the addition of subtasks 8.18 through 8.38.

8.0 DESIGN AND TEST OF CRITICAL COMPONENTS

8.1 Effects of Blade Cooling Alternatives

An automated performance calculation was developed by Carnegie Mellon University to assess the effects of different cooling media and cooling schemes on gas turbine cycle performance. A computer code was also developed for calculating the temperature

distributions over inner and outer blade surfaces for a given expanding gas temperature and coolant inlet temperature and flow. The code performs integrated energy balance and conductive and connective heat transfer calculations for multiple connected blade sections. The code was tested against available first stage turbine blade data.

A survey of recent technical literature on gas turbine blade cooling was performed, as well as a review of NASA reports on an advanced blade cooling system. The reports were helpful in providing information on the performance benefits of internal impingement cooling compared to fin cooling. Recommended procedures for external and internal blade heat transfer coefficients have been outlined for a variety of blade cooling arrangements.

The final report has been completed and is in the process of being reviewed.

8.3 Last Row Turbine Blade Development

The objective of this program is to develop an optimized last stage turbine blade design which will result in acceptable mechanical reliability and enhanced engine performance. The design of the last stage blade was completed. Although this blade met all the design requirements, casting trials revealed transverse columnar grains near the hub section leading and trailing edges. To resolve this problem the lower 15% of the airfoil was redesigned with increased thickness. Analyses are underway to determine the effects of increased thickness on blade frequencies and stresses.

Blade vibration monitor (BVM) system is being developed to allow unobtrusive blade vibration measurement under actual gas turbine engine operating conditions. The data obtained from the BVM is used to calculate and monitor the frequency and response of an entire row of blades. Initial testing of the BVM system was carried out using two probes to measure nonsynchronous vibration of stage 4 blades. Now a 16-probe system is being installed to measure synchronous and nonsynchronous response. The vibration pickup probes were acquired and installed in an engine. Preliminary tests were carried out to verify stage 4 blade vibration characteristics under various operating conditions. The BVM system operation was excellent. Test data analysis is in progress. A more detailed test is planned for August.

8.5 Single Crystal Blade Casting Development

The objective of this program was to develop a single crystal (SC) blade casting for large industrial gas turbines for turbine rows 1 and 3. A review in October 1994 showed row 1 blade castings with persistent "freckling" in the blade root area. Because the number of additional molds needed to achieve acceptable grain structure exceeded the number originally planned for the casting study, casting trials on the thick row 1 blades was discontinued. The thinner row 3 blade castings showed positive grain results so the decision to pursue an acceptable casting was made.

The castability study of large turbine blades in CMSX-4 alloy has been completed at Howmet. One solid and one cored 501FA stage 3 blade with acceptable grain structure have been produced from a total of five trials (with three blades in each trial mold). Visual fluorescent particle, and Laue X-ray diffraction inspections were carried out. Radiographic evaluation and ultrasonic wall thickness measurement indicated that the internal cooling core retained excellent dimensional stability. The results demonstrated that large blades are castable in CMSX-4 SC alloy, although further process development is required to improve the yield. Howmet produced a summary report to document these results.

8.7 Ceramic Materials Development

Ceramic ring segment design is being developed for application on the ATS engine turbine to reduce or eliminate the cooling requirements and enhance engine performance. Parametric finite element modeling was conducted for the 501D5 engine ring segment design. This model was used to analyze the steady state operational thermal loads for the current X45 metal ring segment design and the Continuous Fiber Ceramic Composite (CFCC) design alternative. Several design concepts for 501D5 ceramic composite ring segments were evaluated for overall feasibility and manufacturability. Westinghouse visited DuPont Lanxide Composites, Inc. to assess their manufacturing capability and to discuss specific issues related to the design and manufacture of 501D5 ring segments. DuPont Lanxide delivered 40 test specimens for material properties evaluation.

8.8 Model Diffuser Evaluation and Test

The objectives for this program are: 1) enhance flow uniformity around combustor baskets to help in reducing NOx emissions, 2) optimize air extraction for the IGCC system, and 3) to improve engine efficiency by reducing compressor exit diffuser and combustion cylinder pressure loss.

After the fabrication of the combustion cylinder test model was completed, the model was transported to Clemson University's new Gas Turbine Research Laboratory and installed. A special test rig for measuring combustor basket discharge coefficient of the scaled-down dry low NOx plastic model combustor was fabricated. Test rig commissioning was completed and baseline case testing was started.

Computer codes were written for the automatic pressure measurements via the Scanivalve. The code is used for wall pressure and five-hole probe pressure measurements

Westinghouse witnessed the operation of the test rig and reviewed the results of the computational fluid dynamics (CFD) calculations. To enhance flow distribution in the annular passage between the combustor and the "top hat", it was suggested that the effect of increasing "top hat" height be investigated by CFD analysis. If the CFD analysis show

positive results, a complete set of extended "top hats" will be manufactured and tested. The following CFD calculations have been completed:

- Baseline case for 1/16 domain
- Baseline case for 1/16 domain with the circumferential recess downstream of the prediffuser exit covered up
- 5 and 20% suction at pre-diffuser inlet with the circumferential recess filled
- 5 and 20% suction at pre-diffuser exit with the circumferential recess filled

The CFD results for the "top hat" mass distribution, velocity profiles and static and total pressure profiles are being analyzed. The combustion cylinder flow field is being recalculated using the experimentally determined inlet flow conditions.

8.10 Shroud Film Cooling

The objective of this program is to optimize the turbine stator film cooling design by carrying out a series of tests on a first stage stator plastic model. The model consists of two complete airfoils and a full channel between the two airfoils. Different cooling jet configurations will be tested, each at different flow rates. The heat flux distribution will be measured by using thermochromic liquid crystal technology. The test rig facility and model hardware assembly and debugging was completed at Dynalysis of Princeton. Software for data acquisition and controls was completed but when tested was found to be inadequate. A new compiler did not remedy the situation. It was decided to resolve this by converting from coding in BASIC to FORTRAN. Testing will start after this conversion is completed.

8.11 Directionally Solidified Blade Development

This program was redirected to generating material design property data for DS blade alloys such as CM247 and MARM002. These design data are required to facilitate DS casting technology implementation into large industrial gas turbines. The new program plan includes: (1) determining the effects of chemistry and withdrawal rates on large DS blade castability, and (2) generating long-term creep properties for developing design curves. The new work scope consists of the following tasks:

1. Obtain test material and blades
2. Blank and machine test specimens
3. Perform tensile tests
4. Perform creep rupture tests
5. Perform LCF tests
6. Perform Oxidation tests
7. Evaluation of DS and CC (base line) blades
8. Analyze results and report

Long-term creep rupture testing of 247 Type alloys (Mar M002 and CM-247) in the DS condition has been in progress. HCF tests at 1000°F on M002 DS specimens machined in the longitudinal and the transverse directions are in progress. Conventionally cast Mar M002 test bars in the solution treated condition were procured. The bars are being heat treated. Conventionally cast CM-247 row 3 blades were procured for evaluation. The blades are being machined for test specimens. Burner rig oxidation tests on CM-247LC were performed and the test specimens are being metallographically examined. Burner rig tests are in progress.

8.12 Shrouded Blade Cooling

The stage 3 turbine blade incorporates an interlocked integral tip shroud for performance and mechanical integrity reasons. Temperature and stress considerations necessitate tip shroud cooling, which is complicated by excessive cooling air heat-up as it passes from the blade root to the tip shroud. A successful stage 3 blade cooling design was developed incorporating a central hole to provide shroud cooling air at a suitable temperature. Shroud cooling was accomplished by machining cooling holes, which intercepted the large central hole. The blade and shroud cooling design optimization was completed.

8.14 Closed-Loop Steam Cooling

Closed-loop steam will be a main contributor in achieving greater than 60% ATS plant cycle efficiency. The performance enhancement results from:

1. Increased energy level in the expansion process;
2. More air available for expansion;
3. Cooling air ejection mixing loss elimination; and
4. Improved airfoil performance without surface cooling air ejection.

To make up for the elimination of the protective film barrier on the airfoil surface and hence to produce a successful optimized closed-loop cooling design, the following approaches will be used:

1. Aerodynamic airfoil design will be tailored to minimize gas side heat transfer coefficients.
2. Minimum coolant temperature will be provided.
3. Thermal barrier coatings will be applied on all airfoil surfaces to reduce heat input.
4. The cold side surface area will be maximized.
5. Minimum airfoil wall thickness will be used to reduce the wall temperature gradients and hence reduce the required internal heat transfer coefficients.

Different closed-loop airfoil cooling concepts such as thin wall shell/spar, cored wall casting and spanwise cooling hole were investigated. Modifications to the analytical design tools were incorporated to enhance the accuracy and reduce the time required to analyze

the different cooling schemes. The cooling analysis program capability has been upgraded to include boundary element modeling to enhance thermal conduction modeling.

Work started on identifying and quantifying the relative merits of the two cooling fluids and the different cooling configurations for the Stage1 vane. Viable closed-loop cooling configurations for the airfoil trailing edge were identified. A parametric study was completed on the relationships of the various performance related parameters in closed-loop cooling design based on the thin wall casting concept. Both steam and air were considered as coolants. Cooling flow requirements and heat load estimates for closed-loop steam and closed-loop air cooled systems have been generated for use in cycle performance calculations.

8.15 Active Tip Clearance Control

As an initial effort in the ATS Phase 2 active tip clearance control system development task, available ceramic abradable coatings are being investigated and then applied in an engine demonstration test. These coatings are of the order of 0.050-in. thick. They provide: (1) thermal insulation for the mating, stationary ring segment to minimize required cooling air flow, and (2) a surface for the rotating blade tips to rub against without excessive wear. Initially, no special treatment of the blade tips will be used. Such coatings have been under development for over 15 years by aero gas turbine engine manufacturers and their vendors. They are used in several production aero engines. The purpose of this project is to demonstrate that ceramic abradable coatings can be successfully applied in an industrial gas turbine engine.

A coating vendor, P&W Talon, was selected to coat 501D5 engine stage 1 turbine ring segments. Eight ring segments were coated with an abradable coating and were installed in an engine for field testing. Tip clearance measurements were recorded for future comparison. A boroscope inspection of the abradable coating is planned in eighteen months.

P&W Talon completed shock testing two test pieces. The testing was carried out on a cyclic thermal rig capable of simulating engine heat flux levels. The test results demonstrated that the coating applied for this task exceeded P&W's coating specification for shock resistance.

Two additional sources for providing ceramic abradable coatings are being investigated.

8.16 Flow Visualization Tests

Flow visualization testing was performed at the Westinghouse Power Generation Engineering Laboratories in Casselberry, Florida, using both a single combustor rig and a full-scale sector rig.

These tests were carried out on a modified dry low NO_x combustor using tufts attached to a specially constructed holder, in order to verify qualitatively CFD predictions. The agreement with CFD results was excellent. Effective flow area measurements were carried out on two dry low NO_x combustors, multi-swirl combustor swirl plate, and multi-nozzle combustor pilot.

8.17 Combustion Noise Investigation

Very lean-premix combustion will have to be employed to achieve ultra-low NO_x emission in the ATS engine. This may result in flame instability, combustion generated noise and high vibratory stresses in the combustion system components as well as the downstream turbine airfoils. The objective of this program is to extend the stability range for lower emissions. To achieve this objective an active noise control system is being developed in collaboration with Dr. Ben Zinn of Georgia Tech.

The subscale combustion stability test section design, including modifications required for control valve mounting and for control gas introduced at the proper locations, was completed. The specification for the housing was completed, quotes for the pressure vessel have been received, and fabrication of the combustion stabilization test section pressure vessel has begun. Thermocouples and associated equipment items are on order.

Two candidate methods for measuring volume velocity oscillations in fuel gas lines (i.e., hot-wire anemometers and pressure transducers) are being evaluated. A shaker-driven flow modulator generates the flow oscillations that are to be measured at selected frequencies. These experiments are being conducted in parallel with Westinghouse sponsored analytical work at Carnegie Mellon University on the development of a transfer function to predict volume velocities of combustion products resulting from auxiliary fuel inlet flow velocity fluctuations. A meeting was held with Dr. David Archer of Carnegie Mellon University to define the task of deriving an augmented flame transfer function. This transfer function will be used as a major building block in the overall stabilization system design method. The modulated fuel flow volume velocity measurements will provide the basis for the experimental confirmation of the design method.

8.18 TBC Field Testing

The application of uniform and durable TBC on the turbine airfoil and end-wall surfaces is critical to the design of closed-loop cooling systems. Without the protection provided by the cooling air film in the current cooling designs, the thermal barrier provided by TBC will be very important in maintaining low surface metal temperatures in the ATS engine without requiring high internal heat transfer coefficients. The results of the TBC field test program will provide information on the longevity and effectiveness of the different coating systems.

Twelve 501D5 first stage coated turbine blades were installed in an engine for long term field tests. Four blades were coated with physical vapor deposited (PVD) thermal barrier coating, four with air plasma sprayed (APS) TBC, and four blades with metallic coating only. Inspection of these blades is expected in mid-1996 or mid-1997.

Procurement of 501F first stage turbine blades was initiated. These blades will be coated with TBC (four by APS and four by PVD) and installed in a customer unit fired at 2300°F. Field testing of these blades will provide data that is more relevant to ATS operating conditions.

8.19 Catalytic Combustion Development

Catalytic combustion development is being carried out in collaboration with Precision Combustion Incorporated (PCI) to ensure that single digit NO_x emissions and stable operation are achieved in the ATS engine.

Parametric CFD modeling of the ATS pilot and main swirlers is in progress. CFD modeling results are guiding modifications of the catalytic pilot for ATS operation and development of catalytically stabilized main swirlers. The main swirlers are similar in concept to the catalytic pilot, but the main swirler design is more open and reduces the radical component near the exit to reduce combustor wall interaction/heating.

Work is proceeding on catalytic combustor conceptual designs. In one concept a catalytic pilot is integrated into the catalytic combustor such that the pilot flame assists in stabilizing the premixed fuel/air mixture partially reacted in the catalytic reactor. Exhaust gas recirculation (EGR) is employed to increase the reaction rate over the catalytic reactor section. Two catalytic upper stages are currently envisioned to provide wider turndown. The feasibility of incorporating catalytic reactor(s) into the pilot to eliminate the diffusion flame fuel addition at higher load conditions is being investigated. A fuel preactivator design is being examined to eliminate EGR as a requirement.

A computer program was written to predict NO_x formation for a plug flow catalytic reactor with a downstream stabilization region. Various methane and NO_x reaction mechanisms are being examined for use in the model. The required reactor code modifications to predict emissions from a catalytic combustor with exhaust gas recirculation are being investigated.

8.20 Optical Diagnostics Probe Development

A nonintrusive optical diagnostics probe for measurement of pertinent parameters such as combustion products composition and concentration has been developed. Probe evaluation at pressures up to ten atmospheres was successfully completed. Tests were conducted to quantify temperature effects (up to 570°F) and exposure to 266 nm UV laser

radiation on quartz optical fiber transmissivity. Preliminary results indicate that the optical fiber temperature must be kept below 212°F and/or a longer wavelength source will be necessary. A technique for monitoring the laser beam optical fiber transmissivity was successfully demonstrated.

The optical fiber fuel-air ratio probe was then successfully tested in the Westinghouse's Science and Technology Center plexiglass test rig. The test results showed that approximately 1 in. downstream of the fuel nozzle tip, the "fuel" distribution was very non-uniform. The "fuel" distribution was very uniform in the test section "rich" zone and at the end of the quench zone. These results were consistent with smoke visualization tests, which have been performed previously in this apparatus.

The use of HeCd laser, instead of the pulsed Nd:YAG laser, which has been used to date, was evaluated. Although the optical fiber transmissivity was significantly better with the HeCd laser, the detected signal level was unacceptably low at the available power level. Therefore, it was decided to continue to use the Nd:YAG laser.

A new probe was then fabricated, assembled and tested. The new probe is approximately twice as long as the original probe, incorporates a new metal mirror and a larger collection lens and has a thermocouple located at the tip to measure probe tip temperature.

The system for monitoring the laser beam optical fiber transmissivity was implemented in the original probe and has been successfully employed in the high pressure, high temperature calibration cell.

Probe cooling requirements at typical hot combustion conditions in the high pressure high temperature test facility were evaluated. These tests provide the necessary information to design the probe water cooling system for the hot tests which will be conducted later this year.

8.22 Serpentine Channel Cooling Tests

Internal multi-pass turbine blade cooling configurations were designed to optimize and reduce blade cooling requirements. Plastic models of the cooling schemes have been fabricated and installed in the NASA Lewis test facility to determine internal heat transfer coefficients and pressure drops. A trailing edge cooling circuit model was installed in the test facility, and tested. Test data reduction is in progress. Preparation for the mid circuit model tests has begun.

8.23/8.24 Brush Seal Development

The ATS Phase 2 brush seal development effort consists of: (1) a preliminary investigation to look at the benefits, potential locations, and validation required in applying

brush seals to industrial gas turbine engines, and (2) a focused development effort for one selected engine location, the turbine interstage. EG&G Sealol, Warwick, RI, is the seal vendor selected to support the latter development work. The vendor effort includes: a concept study tribology testing, fabrication of rig hardware, and rig testing of candidate brush seals.

Brush seal development work continued at Westinghouse and EG&G Sealol. Tribopair rig test plan was developed, and the necessary modification were identified to the existing rigs to conduct scaled seal testing. Five different bristle alloys and two different rotor materials were selected for testing. Twenty tribopair tests were to be conducted to characterize ten tribopairs for two rotor surface roughness conditions. Six addition tests will be carried out to study effect of short cycles versus steady state, bristle diameter, and interference.

The tribopair testing is nearing completion. The preliminary results indicate that not coating the mating seal runner is acceptable, if not superior, and that grinding the rotor surface to a smooth finish decreases seal bristle wear.

Design of the candidate seals for rig testing is nearing completion. Bristle wire material was ordered and test rig adaptive hardware was designed.

8.25 High Efficiency Compressor Design

The ATS compressor design philosophy will be based on that used for the advanced 501G compressor, but with additional enhancements. An optimization study conducted on the 501G compressor showed that 16 individually optimized stages will maximize efficiency for the 19:1 pressure ratio design. Continuing the gas path and stage optimization procedure downstream on an additional stages will result in the pressure ratio of the ATS design.

The high efficiency compressor design was started. Inlet guide vane profile shape for low loss at all vane staggers is under investigation. Rotating and stationary airfoil definition for the first six stages is in the process of aero/mechanical iteration. The objective is to satisfy all mechanical constraints without excessive airfoil thickness so as to optimize efficiency. All airfoils will be custom shaped using controlled diffusion design process. To maximize efficiency a new "modified parabolic" shape was defined to minimize losses and maximize incidence tolerance at loadings and Mach numbers common to stages 2 through 16. This basic shape will be cloned throughout the compressor. The inlet strut profile was defined. The profile loss was reduced by reducing the strut thickness. Analysis of the new strut definition found it to be acceptable from both stress and casting considerations. A preliminary inlet guide vane shape was defined.

8.29 Advanced Air Sealing Development

The advanced air sealing development task expands the application of brush seals in Tasks 8.23 and 8.24 to a second location in the ATS combustion turbine engine. The turbine rim is the second location. EG&G Sealol, Warwick, RI, is the seal vendor chosen to support the development work. The vendor effort includes: an initial feasibility test, tribology testing, fabrication of rig hardware, and rig testing of candidate brush seals.

EG&G Sealol began drafting a proposal for a second brush seal development effort for the turbine rim seal location. An initial rig test will be proposed to insure that brush seals can run against interrupted surfaces like the blade platforms in the turbine rim application. Depending upon the results of this initial testing, the turbine rim or an alternate compressor diaphragm location will be chosen for the development.

8.30 Advanced Coating Development

Key to the successful operation of the ATS engine is ceramic thermal barrier coatings (TBC) which must be capable of operation for 24,000 hours on hot section components. The low thermal conductivity of TBC's allows the metal surface temperature of blades and vanes to be effectively reduced to improve life by limiting metal-oxide scale growth. Two methods of TBC application includes air plasma spray (APS) and electron-beam physical vapor deposition (EB-PVD). Each of these TBC application methods produce as-deposited structures with differing properties such as strain tolerance and thermal conductivity. In this program, the optimum bond coat will be combined with the best performing TBC to maximize these properties and hence, provide a coating system with maximum service life at the ATS operating conditions.

Bond coat development is underway. Several candidate ceramic compositions have been identified for the TBC. Air plasma spray deposition trials are now being conducted.

8.32 Ceramic Technology Development

A preliminary design has been identified for the combustor scoops to be manufactured from ceramic composite material. Discussions were held with DuPont Lanxide Composites (DLC) Inc. about this design and about manufacture of test coupons for material characterization.

8.33 Single Crystal Blade Development

The objective of this program is to generate SC materials data for ATS turbine blade design. A detailed plan has been developed for this program. Inquiries have been issued to casting vendors to procure CMSX-4 SC cast slabs for the task of heat treatment

optimization. Reviews with casting vendors and alloy manufacturers have been planned to select candidate heat treatment cycles for the study.

8.38 Steam Cooling Effects on Materials

In the proposed study, a steam chemistry model will be developed to predict types and concentrations of impurities along the turbine gas path to identify the critical stage(s). Then laboratory hot corrosion tests will be conducted on turbine blade and vane alloys in the coated and uncoated conditions at atmospheric pressure for a) an aggressive (100X impurity levels predicted by solubility model), and b) mild environments (10-50X impurity levels predicted by solubility model). The effects of steam with contaminants on high cycle fatigue (HCF) properties of blade alloys will be determined and the design curves will then be established.

The following detailed plan was developed for this program:

1. Define design parameter
2. Collect thermophysical data
3. Evaluate dissociation of steam
4. Collect or generate steam data
5. Calculate solubility of impurities
6. Define environments for testing
7. Develop method to calculate impurities
8. Develop steam chemistry model
9. Define steam chemistry requirements
10. Produce and machine test specimens
11. Coat test specimens
12. Perform corrosion and HCF tests
13. Analyze test results
14. Product report

Howmet was requested to submit a quote for test materials.

SUMMARY

The work performed to date on the ATS Phase 2 Conceptual Design and Product Development Program is as follows:

- All of the candidate testing sites have received NEPA approvals.
- The final configuration chosen for the GFATS cycle has the potential of exceeding the required 60% efficiency (based on the LHV of the fuel), as well as the other SCAP objectives.

- The CFATS studies identified two candidate cycle processes and presented performance and emissions data. A four year development program was outlined for further consideration.
- A market study for the ATS was commissioned and completed during the past year. A topical report will be issued November 1995.
- System definition and analysis was completed for the ATS plant during the past year. Conceptual design of the ATS gas turbine has been completed and all demonstration plant equipment and components identified. A/E design criteria for the ATS plant has been defined and site layout and equipment arrangements drawings prepared. The topical report for this effort is to be issued in November 1995.
- The integrated program plan has been completed and is included in the management plan.
- Phase 2 efforts on the design and development of critical components and materials have progressed and are scheduled to be completed in June of 1996. Following is a brief status of those individual programs:
 - A final report has been completed on the effects of blade cooling alternatives.
 - Last row turbine blade development is in process with detailed testing scheduled for the latter part of 1995 using a newly developed blade vibration monitoring system.
 - Acceptable results have been obtained in the casting of single crystal blades for turbine blades rows 1 and 3 using CMSX-4 alloy.
 - Ceramic ring segment design and development using continuous fiber ceramic composites is continuing with materials properties evaluation ongoing.
 - Model diffuser evaluation and test at Clemson University is continuing with the fabrication of a test rig after modeling and analysis with CFD sections of the combustion cylinder.
 - A first stage turbine stator plastic model has been built for the test of shroud film cooling. Data acquisition software is being modified and testing will start when conversions are completed.
 - Directionally solidified blade development continues with various tests being performed on 247 type alloy specimens.
 - A successful stage 3 cooling design was developed for the interlocked integral tip shroud design.
 - Closed-loop cooling design configurations have been identified. Parametric studies have been completed on the relationships of various performance related parameters based on the thin wall casting concept. Cycle performance calculations have been made based on cooling flow requirements and heat load estimates for both coolants.

- An active tip clearance control conceptual design has been made. In addition, to optimize tip clearance control, field tests are under way using ceramic abradable coatings that have been successfully used in aeroengines.
- Combustor rig flow visualization tests have been conducted for two dry low NO_x combustors, a multi-swirl combustor swirl plate, and a multi-nozzle combustor pilot.
- Combustion noise investigation is being performed in parallel with the development of an active noise control system at Georgia Tech and the development of the subscale combustion stability test rig.
- Thermal barrier coating long term field tests have begun with both blades coated using physical vapor deposition and air plasma spray technologies.
- Conceptual designs are being developed for catalytic combustors along with a computer program to predict NO_x formation for a plug flow catalytic reactor with a downstream stabilization region.
- A nonintrusive optical diagnostics probe for measurement of pertinent parameters such as combustion products composition and concentration has been developed and tested at pressures to 10 atms. and temperatures to 570°F. A probe with a water cooling system will be developed for hot tests to be conducted later in 1995.
- Internal multi-pass turbine blade cooling configurations have been designed. Plastic models of 1st stage blade internal multi-pass turbine blade cooling configurations were fabricated and installed at the NASA Lewis test facility. A trailing edge circuit model was installed and tested with data reduction in progress. A mid-circuit model is now being prepared for test.
- Brush seal development continued with tribopair testing of different seal materials with different rotor materials and surface roughness conditions. Rig testing is being prepared with the design of candidate seals and adaptive test rig changes. A second brush seal development effort for the turbine rim seal location was also begun.
- The high efficiency compressor design was started. The design philosophy is based on that used for the 501G with additional stages added at the compressor rear to increase the pressure ratio.
- An advanced coating development program was started to develop a ceramic composition bond coat to use with the best performing TBC now under test.
- Materials data generation for single crystal CMSX-4 heat treatment optimization was begun.