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

**Quarterly Report
May - July 1995**

August 1995

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
CONCEPTUAL DESIGN AND PRODUCT DEVELOPMENT

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August 1995

QUARTERLY STATUS REPORT

Date: August 22, 1995
Report No. TPR-08
Reporting Period: May-July 1995

CONTRACT TITLE AND NUMBER: Advanced Turbine Systems Program --
Conceptual Design and Product
Development DE-AC21-93MC30247

CONTRACTOR'S NAME: Westinghouse Electric Corporation
Power Generation Business Unit
4400 Alafaya Trail
Orlando, FL 32826-2399

CONTRACT PERIOD: August 5, 1993 to July 5, 1996

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

Task completed.

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

Task completed.

5.0 MARKET STUDY

The initial market study results were reviewed. Final market study report will be completed in November.

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. Mr. D. Horazak of Gilbert/Commonwealth Inc. described the ATS plant design. There were no major issues raised with either the engine or the plant designs. However, the reviewers identified a number of action items and recommendations to enhance the ATS engine design and suggested future tradeoff studies to optimize the plant design.

8.0 DESIGN AND TEST OF CRITICAL COMPONENTS

8.1 Effects of Blade Cooling Alternatives

The final report has been completed and is 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 with an interlocked tip shroud and a part span snubber 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 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, radiographic and Laue X-ray diffraction inspections were carried out. 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 first two ATS engine turbine stages to reduce or eliminate the cooling requirements and enhance engine performance. Several design concepts for 501D5 ceramic composite ring segments were evaluated for overall feasibility and manufacturability. Mr. Evan Ludeman 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 Combustion Cylinder Flow Mapping

The installation of the combustion cylinder test model in the Clemson University Gas Turbine Research Laboratory was completed. Instrumentation installation was completed, all pressure lines were checked for leaks and the automatic traversing system was tested to ensure satisfactory operation. Test rig commissioning was completed and baseline case testing was started.

Dr. William Ryan of Westinghouse visited Clemson University to discuss progress on this project. He witnessed the operation of the test rig and reviewed the results of the CFD calculations. To enhance flow distribution in the annular passage between the combustor and the "top hat", he suggested that the effect of increasing "top hat" height be investigated by CFD analysis. If these results show positive results, a complete set of extended "top hats" will be manufactured and tested.

The following CFD calculations have been completed:

1. Baseline case for 1/16 domain
2. Baseline case for 1/16 domain with the circumferential recess downstream of the pre-diffuser exit covered up
3. 5 and 20% suction at pre-diffuser inlet with the circumferential recess filled
4. 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 test data acquisition software 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. The test specimens have been in tests for over 8400 hours. 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 at 1750°F and the test specimens are being metallographically examined. Burner rig tests at 1850°F 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 large 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 or air cooling will be the 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.

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.

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. Cooling designs based on the spanwise cooling hole concept are being investigated. This will provide information for evaluating the relative merits of cored wall casting, shell-spar, and spanwise cooling hole concepts.

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 tests were carried out on a modified dry low NOx 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 NOx 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 NOx 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 to ensure that single digit NO_x emissions and stable operation are achieved in the ATS engine.

Mr. Dave Amos visited Precision Combustion Inc. to review progress on this program. The review covered (1) CFD results on the catalytic pilot and main swirlers for the Multiple Catalyst Swirl Stabilized Burner (MCSSB), (2) Advanced Catalytic Combustor with integrated catalytic pilot and EGR design drawings, (3) results from related experimental program for methane and dual methane/Jet-A catalytically enhanced combustors, and (4) results from PCI's flashback arrestor development program.

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 MCSSB 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.

Computer program is 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.

8.20 Optical Diagnostics Probe Development

The optical fiber fuel-air ratio probe was successfully tested in the Westinghouse STC 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 has been 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 has been 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

Mr. Ed North and Mr. Ralph Matthews visited NASA-Lewis Research Center to witness a preliminary test run to review the test procedure, and to review the data acquisition and presentation.

Trailing edge model testing has been completed and 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 modifications 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 additional 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.

Dr. Ray Chupp presented a technical paper describing the brush seal development program at the AIAA conference.

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. The 501G compressor is a new aerodynamic design using controlled diffusion airfoils (CDA), reduced number of stages, and reduced airfoil thickness. 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 three stages will result in the 25:1 pressure ratio 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 (EG-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, its ATS performance.

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

Significant effort was spent on planning the ATS Phase 2 ceramic component development program. Milestones and schedules have been identified. 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 single crystal (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 for heat treatment optimization. Reviews with casting vendors and alloy manufacturers are planned for next month to select candidate heat treatment cycles for the study.

8.37 Shaft and Disk Welding

The objective of this program is to develop the welding for Ni-based discs. Discussions were held with Oak Ridge National Laboratory and Ohio State University concerning their possible involvement in the rotor welding development task. Either facilities could assist in determining the weldability of the rotor material, developing a model to simulate the welding process, selecting the optimum welding processes, and verification weld tests. Additional information was obtained about the materials considered and the welding processes through a literature search and vendor contact.

8.38 Steam Cooling Effects on Materials

In the proposed study, 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's 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.

PLANS FOR THE NEXT REPORTING PERIOD

Task

- 5.0 Complete the final report on the ATS Market Study.
- 6.0 Produce topical report on the ATS engine and plant conceptual designs.
- 8.1 Review the final report.
- 8.3/8.13 Continue last stage turbine blade and BVM system development.
- 8.5 Review Howmet report.
- 8.7 Develop design concepts for the proposed CFCC ring segment design and select the optimum design.
- 8.8 Complete the basic air model test at Clemson University and initiate additional testing.
- 8.10 Complete model tests at Dynalysis.
- 8.11 Generate material property data for CM247 and M002 DS materials.
- 8.12 This task has been completed.
- 8.17 Start active noise control concept verification testing.
- 8.18 Install 501F coated blades in host engine for field testing.
- 8.19 Continue conceptual exploration on catalytic combustion technology.
- 8.20 Continue optical diagnostics probe development.
- 8.22 Start tests on the mid circuit cooling circuit model at NASA Lewis.
- 8.23/8.24 Continue brush seal development.
- 8.25 Design high efficiency compressor.
- 8.29 Continue advanced air sealing development.

- 8.30 Develop advanced coating system for ATS engine.
- 8.32 Develop technology for ceramic components.
- 8.33 Generate single crystal materials data.
- 8.37 Develop welding process for Ni-based discs.
- 8.38 Develop steam chemistry model to predict types and concentrations of impurities.

Ronald L. Bannister
Program Manager

Attachments:

Request for Patent Clearance for Release of Contracted Research Documents (Form METC F 1332)
U.S. DOE, METC Contract Report Transmittal Checklist