Advanced Turbine Systems Program Conceptual Design and Product Development

**Quarterly Report
February - April 1995**

June 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

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ple

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, 175 Oak Ridge Turnpike, Oak Ridge, TN 37831; prices available at (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

Advanced Turbine Systems Program Conceptual Design and Product Development

**Quarterly Report
February - April 1995**

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

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Westinghouse Electric Corporation
Power Generation Business Unit
4400 Alafaya Trail
Orlando, Florida 32826-2399

June 1995

QUARTERLY STATUS REPORT

DATE:	June 29, 1995
REPORT NO.:	TPR-07
REPORTING PERIOD:	February-April, 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 January 6, 1996

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

Task completed.

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

Task completed.

3.0 MARKET STUDY

Market study is in progress with completion date targeted for June.

4.0 SYSTEM DEFINITION AND ANALYSIS

The ATS gas turbine and plant flange-to-flange conceptual designs are proceeding.

5.0 DESIGN AND TEST OF CRITICAL COMPONENTS

Effects of Blade Cooling Alternatives

An automated performance calculation is being developed by Carnegie Mellon University to assess the effects of different cooling media and cooling schemes on gas turbine cycle performance. Recommended procedures for external and internal blade heat transfer coefficients have been outlined for a variety of blade cooling arrangements. Started work on the final report preparation.

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. 3-D finite element analysis on the final blade geometry was completed. Casting trials are under way to determine the feasibility of a shrouded blade with a mid-span snubber.

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 in April. Field tests will be carried out to verify the Stage 4 blade vibration characteristics under various operating conditions and to make enhancements to the BVM system where required.

Single Crystal Blade Casting Development

The objective of this program is to develop a single crystal blade casting for large industrial gas turbines. The fifth mold of three Row3 shrouded blade was built in February. This mold incorporated improvements in the grain starter and ramp areas to suppress the secondary grain formation detected in the previous mold. One of the three blades from the fifth mold exhibited good grain structure based on visual, fluorescent penetrant and Laue X-ray diffraction inspections. Radiographic evaluation and ultrasonic wall thickness measurement indicated that the internal cooling core retained excellent dimensional stability.

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. Analysis and post processing were carried out on the steady state operational thermal loads for the current metal ring segment design and the Continuous Fibre Ceramic Composite (CFCC) design alternative. Work continued on developing alternate conceptual designs for the CFCC ring segment.

Combustion Cylinder Flow Mapping

The combustion cylinder test model was transported to the Gas Turbine Research Laboratory and installed. Traversing mechanism for the fivehole probe was completed. Instrumentation installation was completed. Air extraction ducting has been installed.

Discharge coefficient (C_D) tests on the true scale model of the dry low NO_x combustor and the simulated baskets have been completed. To match the true model C_D , a 4.2 in. diameter orifice was required for the simulated baskets. These orifices were installed in all 15 simulated baskets and tested to verify the C_D values for each basket.

Shakedown testing has commenced. Two test runs were carried out at the maximum flow rate of 17,000 CFM. Pressure drops were measured between the important subsections in the combustion cylinder. The flow profile at prediffuser inlet was measured and found to be peaked near the inner diameter. This profile will be reviewed by Westinghouse, and a decision will be made if profile modification is required.

CFD analysis for the 1/4 (90°) domain of the combustion cylinder flow field is almost complete. Griffith diffuser design is continuing. Suction will be applied at pre-diffuser exit without changing the wall contour. A case simulating 20% suction at prediffuser inlet has been run, and a case with 20% suction at pre-diffuser exit is

almost complete. CFD results show that covering the circumferential gap at pre-diffuser exit inner wall results in a 22% reduction in the total pressure loss (0.4 percentage points of pressure loss). This modification will be incorporated in actual engine hardware.

Shroud Film Cooling

To optimize turbine stator shroud film cooling design, a series of plastic model tests will be carried out. The test facility and model hardware debugging was completed. Software for data acquisition and controls was completed. Data reduction software for interpreting the video tape recordings of the thermochronic liquid crystals is being developed. Testing will start in May.

Directionally Solidified Blade Development

This program was redirected to generating material design property data for DS blade alloys such as CM247 and MARMOOZ. 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. Long-term creep rupture testing on DS CM247 and MAR MOOZ test specimens has been in progress for over 6,500 hours. To evaluate the effects of chemistry and withdrawal rates on DS material microstructure and mechanical properties, test slabs and blades were ordered.

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 refinement is nearing completion.

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.

Different closed-loop airfoil cooling concepts such as shell/spar, cored wall casting and spanwise cooling hole are being investigated. Work started on identifying and quantifying the relative merits of the two cooling fluids and the different cooling configurations for the Stage 1 vane. Viable closed-loop cooling configurations for the airfoil trailing edge were identified using spanwise cooling holes. The parametric study has been 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. Optimal values of critical design parameters such as coolant flow rate, airfoil trailing edge radius, and cooling channel geometry were determined for different values of coolant supply temperature, coolant pressure drop, and maximum allowable surface metal temperature. The results will be used in cycle performance estimations.

Active Tip Clearance Control

As an initial effort in the ATS Phase2 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. They will be installed in a 501D5 engine for field testing. P&W Talon will also coat a test piece, which will be shock tested in a rig to demonstrate that the coating will stay attached to the ring segment after several simulated engine startup and shut down cycles.

Flow Visualization Tests

Flow visualization testing was performed at the Westinghouse Power Generation Engineering Laboratories in Casselberry, Florida. Westinghouse is now utilizing spark generators by inserting them into the flow field to study bulk flow patterns. This has been done in both single combustors and in a fullscale sector rig.

Combustion Noise Investigation

Very lean premix combustion will have to be employed to achieve ultralow 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.

Design requirements and conceptual design for a subscale combustion stability test section for control system evaluations have been established and the detail design is in progress. A fuel/air premix swirler has been added to the test section design as recommended by DOE-METC. Dynamic analyses were performed to predict the frequency response of valve-modulated flows through fuel nozzles. Tests are under way for comparison of pressure transducer and hot-wire measurements of gas flow oscillations.

TBC Field Testing

The application of uniform and durable TBC on the turbine airfoil and endwall 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 Stage 1 turbine blades were coated (four blades with metallic bond coat plus air plasma sprayed TBC coating, four with metallic bond coat plus physical vapor deposited TBC, and four with metallic bond coat only). TBC thickness was

measured. This information will be used for comparison with thickness distribution after field service to quantify any coating loss due to erosion. The twelve blades will be installed in a 501D5 engine in the third quarter of 1995.

Catalytic Combustion Development

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

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 was written to predict NOx formation for a plug flow catalytic reactor with a downstream stabilization region. Various methane and NOx 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.

Optical Diagnostics Probe Development

Continued development of nonintrusive optical diagnostics probe for measurement of pertinent parameters such as combustion products composition and concentration. 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 has been successfully demonstrated. Ways to incorporate this into the probe design are being investigated.

Serpentine Channel Cooling Tests

Trailing edge cooling circuit model (see Figure 1) has been installed in the test facility, and shakedown testing is under way. Initial test results showed that the trailing edge exit holes choked at one offdesign condition (increased flow with blockage of some holes). The holes will be opened up to alleviate this situation.

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 will 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. Hardware manufacture for tribopair testing has been completed.

PLANS FOR THE NEXT REPORTING PERIOD

Task

- 5.0 Complete marketing survey on ATS.
- 6.0 Complete the conceptual design of the ATS gas turbine and plant.
- 8.1 Complete final report on the automated performance calculation system development.
- 8.3/8.13 Continue last row turbine blade development.
- 8.5 Evaluate the results of the last Row 3 mold castings.
- 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 Continue shroud cooling concept evaluation.
- 8.17 Start active noise control concept verification testing.
- 8.18 Install all 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 trailing edge cooling circuit model at NASA Lewis.
- 8.23/8.24 Continue brush seal development.

R. L. Bannister
Program Manager

ATTACHMENTS:

Figure 1

Request for Patent Clearance for Release of Contracted Research Documents
(Form METC F 1332)

U.S. DOE, METC Contract Report Transmittal Checklist

501G Row 1 Blade Trailing-Edge Test Model