UTILITY ADVANCED TURBINE SYSTEMS PROGRAM (ATS)

TECHNICAL READINESS TESTING AND

PRE-COMMERCIAL DEMONSTRATION

CONTRACT NO. DE-FC21-95MC32267

FINAL

QUARTERLY TECHNICAL PROGRESS REPORT TPR-22
For the Period July 1, 2001 to September 30, 2001

to the

U.S. DEPARTMENT OF ENERGY

Office of Fossil Energy

National Energy Technology Laboratory

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Submitted by

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DISCLAIMER

ABSTRACT

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. Specific performance targets have been set using natural gas as the primary fuel:

- System efficiency that will exceed 60% (lower heating value basis) on natural gas for large scale utility turbine systems; for industrial applications, systems that will result in a 15% improvement in heat rate compared to currently available gas turbine systems.
- An environmentally superior system that will not require the use of post combustion emissions controls under full load operating conditions.
- Busbar energy costs that are 10% less than current state-of-the-art turbine systems, while meeting the same environmental requirements.
- Fuel-flexible designs that will operate on natural gas but are capable of being adapted to operate on coal-derived or biomass fuels.
- Reliability-Availability-Maintainability (RAM) that is equivalent to the current turbine systems.
- Water consumption minimized to levels consistent with cost and efficiency goals.
- Commercial systems that will enter the market in the year 2000.

In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plant is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design.

This report summarizes Phase III Extension activities for a three month period. Additional details may be found in monthly technical progress reports covering the period stated on the cover of this report. Background information regarding the work to be completed in Phase III may be found in the revised proposal submitted in response to A Request for Extension of DE-FC21-95MC32267, dated May 29, 1998 and the Continuing Applications of DE-FC21-95MC32267, dated March 31, 1999 and November 19, 1999.

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EXECUTIVE SUMMARY

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. In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plant is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318 MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design. This report summarizes Phase III activities for the three month period July 1, 2001 to September 30, 2001.

Phase 3 Extension originally involved no load testing of the ATS turbine generator. A redefinition of Phase 3 Extension tasks was submitted as a continuing application to the Department of Energy on March 31, 1999. The continuing application continues to focus on critical engineering, manufacturing, development and testing to verify the readiness of ATS technology for commercial application. Approval of the continuing application was received in June 1999. A second continuation application was submitted in November 1999.

Agilis completed the 3-D model for the test vane and work on the thermo-mechanical analysis for the vane cascade test has begun. A set of water spray nozzles has been incorporated into the exhaust elbow design. TurboSpecialists have completed manufacture of the instrumentation section.

Turbine test data has been analyzed. Thermal efficiency has been calculated for all vane and blade clocking positions and plots of efficiency versus clocking position have been created. A comparison of the mechanical and thermal efficiencies has been conducted.

For the turbine blade root verification program, Hamilton has not completed the test disc machining. The testing at STC will have to be completed with SWPC funding.

For the combustion system, ATCC Modules #3 and 4 were tested at DLR. Due to air leakage, exact air flow could not be determined. The light-off temperature for Retallick's Pd coating was tested and found to be higher than for PCI's coating.

Testing of the rope seal at the Millennium site was inconclusive due to a damaged seal. A new seal has been installed. Field testing of the new abradable coating (75% / 25% Ni/Gr) with the HVOF bond coat process is scheduled for November.

Advanced coating development continued with an evaluation of the feasibility of co-depositing 8YSZ along with a compound expected to improve the sintering resistance. It was concluded that introduction of additives during the TBS deposition was not successful in improving the sintering resistance.

As part of the turbine optimization effort, the turbine rake test at Lakeland was completed. Data from the test will be used for aerodynamic turbine enhancements and CFD code calibration. Turbine stage 1 and 2 tip clearance testing at Millennium was completed. Data from the test will be used to set final tip clearance.

Due to modeling issues with transonic flows, the compressor optimization of row 1 and 2 blades have progressed slowly. The compressor traverse test has been completed and the data is being analyzed. This data will be used for redesign efforts and CFD calibrations. A new rope seal has been installed at Millennium.

The findings of a root cause analysis into the degradation mechanisms of BFH coating indicate the most likely cause to be thermal mismatch between the ceramic backfill and the honeycomb. The results of heat flux testing indicate that retention of ceramic backfill is critical due to rapid oxidation of the uncovered honeycomb. Due to the results of the W501D5 engine test of BFH it was concluded that the thermal limit for BFH is less than initially believed. Evaluation of the extent of oxidation of the metal honeycomb revealed that the "exposed" honeycomb at the hot surface experiences the most oxidation and that oxidation was most severe in regions not protected by ceramic backfill.

Phase 3 rejuvenation study of alternate alloy PWA 1483 creep rupture tests have been completed and the data is being analyzed. Two reports have been issued for Phase 2 and Phase 3 studies.

PCC has completed nine casting trials of the row 1 blade and vane alternative designs. Inner and outer shroud molds from trial 9 produced successful results while the airfoil molds had mixed results. The first fully machined inner shroud sliced skin was received and showed limited distortion. Metem has reportedly completed STEM drilling of airfoil cooling features. Tests of mismatched bond joints indicate that significant tilt misalignments negatively impact joint performance. Additional testing of smaller bonded samples is ongoing.

The planned catalytic coating screening tests have been completed. A standard coating specification, to be provided to selected vendors, has been prepared. Module 1 has completed shaker table testing, running at about 1 g rms for a 450 to 500 Hz band for 100 hours. Initial examination of the tubes suggested the possibility of air cracks. However, more detailed examination indicates that the tube damage is not a result of fatigue failure but due to wall leak paths in the brazing. Full basket studies and prliminary evaluations

have been completed. The catalytic combustor costs appear competative with Dry Low NOx and SCR under ATS application.

Demobilization of the Lakeland site and restoration of the W501G unit have been completed. The test trailers were removed and all unnecessary instrumentation has been removed. Instrumentation routing holes in the cylinder have been sealed.

INTRODUCTION

BACKGROUND

The National Energy Strategy (NES) calls for a balanced program of greater energy efficiency, use of alternative fuels, and the environmentally responsible development of all U.S. energy resources. Consistent with the NES, an U.S. Department of Energy (DOE) program has been created to develop Advanced Turbine Systems (ATS). The Siemens Westinghouse ATS Program is funded and directed by DOE's National Energy Technology Laboratory (NETL). The technical ATS requirements are based upon two workshops held in Greenville, SC that were sponsored by DOE and hosted by Clemson University. The objective of this 8-year program, managed jointly by DOE's Office of Fossil Energy and Office of Conservation and Renewable Energy, is to develop natural-gas-fired base load power plants that will have cycle efficiencies greater than 60%, based on lower heating value (LHV), be environmentally superior to current technology and also be cost competitive. The program will include work to transfer advanced technology to the coal-and biomass-fueled systems being developed in other DOE programs.

METHODOLOGY

The Advanced Turbine Systems program is structured into four elements:

- Innovative Cycle Studies
- Utility Advanced Turbine Systems
- Industrial Advanced Turbine Systems
- Technology Base

Within each program element there are several planned phases. For example, the Innovative Cycle Studies element includes two phases.

- Program Definition/Planning Studies
- Concept Development

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. Specific performance targets have been set using natural gas as the primary fuel:

- System efficiency that will exceed 60% [lower heating value (LHV) basis] on natural gas for large-scale utility turbine systems; for industrial applications, systems that will result in a 15% improvement in heat rate compared to currently available gas turbine systems.

- An environmentally superior system that will not require use of post-combustion emissions controls under full-load operating conditions.

- Busbar energy costs that are 10% less than current state-of-the-art turbine systems, while meeting the same environmental requirements.

- Fuel-flexible designs that will operate on natural gas but are also capable of being adapted to operate on coal-derived or biomass fuels.

- Reliability-Availability-Maintainability (RAM) that is equivalent to the current turbine systems.

- Water consumption minimized to levels consistent with cost and efficiency goals.

- Commercial systems that will enter the market in the year 2000.

In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plants is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318 MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design. Phase III extension activities focus on critical engineering, manufacturing development, and testing to verify the readiness of ATS technology for commercial applications.

This report summarizes Phase III extension activities for a three month period. Additional details may be found in monthly technical progress reports covering the period stated on the cover of this report. Background information regarding the work to be completed in Phase III may be found in the revised proposal submitted in response to A Request for Extension of DE-FC21-95MC32267, dated May 29, 1998 and the Continuing Applications of DE-FC21-95MC32267, dated March 31, 1999 and November 19, 1999.

RESULTS AND DISCUSSION

11.0 PROGRAM MANAGEMENT

There were no scheduled activities for this quarter.

12.0 DEVELOPMENT ENGINEERING

12.1 VERIFICATION TESTS

Vane Cascade The 3-D model for the test vane was completed by Agilis and they began work on the thermo-mechanical analysis of the test vane and side wall vanes. In order to reduce the exhaust elbow cost by using less expensive material, a set of water spray nozzles will be incorporated at the exhaust elbow inlet. TurboSpecialists has completed the manufacturing of the instrumentation section. The exhaust duct will be completed by mid-October. Components that were previously manufactured and stored at W. Schmidt were refurbished and shipped to TurboSpecialists along with transition mouth seals and vane shroud side seals.

Turbine Test Data Analysis Thermal efficiency was calculated for all vane and blade clocking positions and at discrete radial positions. Plots of efficiency versus clocking position were generated for both vane and blade rows. Turbine speed and acceleration data were also analyzed and assessed. Based on the speed data and the torque measurements, the mechanical efficiency was calculated for both vane and blade row clocking data. A comparison of the mechanical and thermal efficiencies was then conducted.

Turbine Root Blade Verification Hamilton has not completed the test disc machining by the end of July. The testing at STC will have to be carried out after the ATS program completion and paid for by SWPC.

Turbulator Model Tests No scheduled progress to report.

12.2 C. T. ENGINE DEVELOPMENT ENGINEERING

Combustion System Development ATCC Modules #3 and 4 were tested at DLR. Air leakage in the rig made it impossible to determine the exact air flow through the module and caused problems with flame stability and emissions measurment. No damage to the hardware occurred. The modules and rig liner are being returned to Orlando. The liner design will be revised to reduce the leakage. The modules will be used for minimizing tests in the atmospheric test rig at Casselberry. We are waiting for a quote from PCI on the catalyst for Module #5. The seven-tube reactor with Retallick's Pd coating was tested at STC. The light-

off temperature for the catalyst was much higher than for PCI's coating (500° C vs 350° C). However, once the catalyst lit off, a significant temperature rise was generated.

Advanced Seal Development

Rope Seal Field-testing to quantify the flow savings associated with the rope seal at Millennium were inconclusive due to a damaged rope seal. A new rope seal was installed and additional testing is to be completed in October or November.

Abradable Coating Development Field testing of the new coating (75%/25% Ni/Gr) with the HVOF bond coat process is scheduled to begin in November. In addition, the development of a new turbine abradable system is being investigated due to the inability of the present systems to provide good abradable results with over 200 hours of aging.

Labyrinth Seal No scheduled progress to report.

Brush Seal Development No scheduled progress to report.

Advanced Coating Development A preliminary evaluation was completed to determine the feasibility to co-deposit a compound expected to improve the sintering resistance along with 8YSZ. This was performed for both EB-PVD and APS. For the EB-PVD coatings, single crystalline columns could not be obtained due to the introduction of an additional compound. Inter-columnar spaces were reduced relative to standard EB-PVD 8YSZ and, due to the polycrystalline nature of the columns, the sintering resistance was worse than for 8YSZ. For the APS coatings, the coating density increased significantly due to the introduction of the additive. Therefore, it was concluded that introduction of additives during the TBS deposition was not successful in improving the sintering resistance.

Turbine Optimization Turbine exhaust rake test was completed at Lakeland. Data reduction of results and CFD calibrations are under way. This data will be used for aerodynamic turbine enhancements and CFD code calibration. Row 1 and 2 turbine blade evaluations show that increased rotor cooling air (RCA) temperature is acceptable with regard to creep and oxidation. RCA temperature study showed a 405°F temperature limit due to turbine disk 4 stresses. Turbine stage 1 and 2 tip clearance testing was completed at Millennium. Data from the test will be used for setting final tip clearance and developing methods for base-load tip clearance minimization. Row 1 blade ring TBC development will also depend upon these results.

Compressor Optimization Compressor blade 1 and 2 redesign efforts have progressed slowly due to modeling issues with transonic flows. New modeling techniques are being implemented. Compressor traverse test was completed at Lakeland. Data reduction of results and CFD calibrations are under way and will

be used for redesign efforts on the compressor front stages. Redesign components will be retrofittable and will improve compressor efficiency. Rope seals were installed at Millennium and are presently in operation. Malfunctioning annubar was repaired and will provide measurements on performance benefit associated with rope seals and vane 2 modulation.

12.3 MATERIALS DEVELOPMENTAL ENGINEERING

DS/CC Material Properties Final report, TR-01175, was issued. See Task 12.3.11 LCF/TMF of Vane and Blade Alloys.

Steam Effects on Materials Final report, TR-01176, was issued.

Production Support of SX Casting PCC is building molds for casting trial #7. The FTT team had their kick-off meeting on the W501GS row 1 vane development.

Advanced Vane Alloy This task is complete.

TBC Life Prediction No scheduled tasks.

ATS NDE This task is complete.

TMF Testing Row 1 Blade Alloy Final report, TR-01175, was issued. See Task 12.3.4 DS/CC Material Properties.

Ring Segment Abradable Coating Development A root cause analysis was conducted to identify potential degradation mechanisms for the BFH coating in the W501D5 engine test. The most likely cause was identified as thermal mismatch between the ceramic backfill and the honeycomb. Short-term high heat flux testing of 1) BFH cells completely filled with ceramic backfill and 2) BFH cells only half filled was conducted to evaluate the impact of "loss of ceramic backfill" on honeycomb degradation. The results indicate that retention of ceramic backfill is critical to the durability of the BFH coating system. Unprotected, the honeycomb rapidly oxidizes and degrades at temperatures >1300°C.

Thermal Limits of BFH Based on the results of the W501D5 engine test of BFH it was concluded that the thermal limit for BFH is less than initially believed. Thus, it was agreed not to proceed with the High Pressure Burner Rig Testing of BFH at NASA Glenn Space Center. Evaluation of the extent of oxidation of the metal honeycomb under thermal gradient conditions revealed that the "exposed" honeycomb at the hot surface experiences the most oxidation. The oxide remains very adherent and thin for BFH subject to a hot surface temperature of 1200°C for 200 hours. Additionally, honeycomb oxidation was found to be more severe in

regions not protected by ceramic backfill. Materials for fabricating test rings were not received until the week of September 24th. Time did not permit any fabrication or testing before the end of the program.

Alternate Alloy Development For Phase 3 – rejuvenation study of PWA 1483, the creep rupture testing of specimens in baseline, strain degraded and rejuvenated conditions have been completed and the data is being analyzed. In addition, Phase 2 test data on heat treatment effect on PWA 1483 properties have been analyzed. Two reports, "Effect of Thermal Processing on PWA 1483 Material Properties" and "Rejuvenation of PWA 1483 Single Crystal Components" covering Phase 2 and Phase 3, respectively, were issued in September.

BFH for Hot Walled Combustors No scheduled activity.

12.4 C. T. MANUFACTURING ENGINEERING

Row 1 Blade and Vane Alternative Design

Casting PCC has completed 9 casting trials. Inner and outer shroud molds from Trial 9 produced successful results. The parts had complete fill and appear to have no significant defects. Airfoil molds had mixed results. Some parts exhibited 100% fill while other parts exhibited similar run-out issues as seen in previous trials.

Manufacturing The first fully machined inner shroud sliced skin was received. The parts were machined with cooling channels. Limited distortion occurred, but the parts fit well when clamped with small force. Bonding fixture manufacturing continues. All four inner shroud assemblies have had the simulated cooling features machined. Metem has reportedly completed STEM drilling of airfoil cooling features in the second cobalt vane. Metem was asked to take several cross-sections from the airfoil for further evaluation.

Mechanical Properties Intentionally mismatched bond joints were fabricated for testing. A majority of these joints have been tested with results to date indicating that significant tilt misalignments negatively impact joint performance. Additional smaller bonded samples are currently being bonded and micro-structurally evaluated to verify the bondline features/structures observed in the larger misaligned test blocks. The recrystallization (RX) study is nearing completion. Both micro-structural and mechanical property results have been obtained for fine surface layer RX (handling-induced) and deep large RX grains (cold work/mold-induced).

12.5 GENERATOR DEVELOPMENTAL ENGINEERING

ATS Class G Stator Development No scheduled activity.

12.6 ADAPTATION TO COAL AND BIOMASS FUELS

The draft topical report describing the ATS turbine in coal-fueled applications was transmitted to DOE.

13.0 C. T. MANUFACTURING DEVELOPMENT AND TOOLING

13.1 DELETED

13.2 MANUFACTURING & TOOLING DEVELOPMENT ENGINEERING

No scheduled activity.

13.3 DELETED

13.4 MANUFACTURING VERIFICATION TESTS

No scheduled activity.

14.0 ATS TECHNOLOGY VERIFICATION PROGRAM

14.1 STEAM COOLED COMPONENT & AERO-THERMAL DESIGN VALIDATION TEST

Test and Instrumentation Decommissioning The Lakeland W501G was the prototype unit for the W501G fleet and contained an extensive amount of instrumentation for testing purposes. The majority of the testing performed was related to projects funded by the government through the ATS project. A portion of the ATS funding was also allocated for demobilization of the Lakeland site and restoration of the unit. These 2 objectives were accomplished over the past few months. The test trailers were removed from the site and all unnecessary instrumentation has been removed from the unit. Instrumentation routing holes in the cylinder have been plugged and seal welded in order to return the unit to a standard configuration.

14.2 ADVANCED VISCOUS COMPRESSOR TEST

Task is complete.

14.3 CATALYTIC COMBUSTOR TEST

Catalytic Coatings/Materials Qualification Completed planned catalytic coating screening tests, report prepared. Prepared standard coating specification that will be provided to selected vendors. Completed initial phase of long term substrate oxidation exposure testing.

Subscale Module Testing Fabrication of 7SSMod3 (Pt coating) completed. Completed testing of 7-tube, Pd-based module (7SSMod2). No substantial catalytic reaction was achieved. Plans are to install PCI module (TW5-6 coating) and benchmark.

Module Development The QA/QC data from PCI on flared tube dimensions was reviewed and accepted. Received delivery of PCI supplied coated tubes (TW6-5S) to complete fabrication of 306FSMod5 module.

Completed shaker table testing on Module 1, running the base-motion model at about 1 g rms for a 450 to 500 Hz band for 100 hrs. Disassembled the module and inspected. The initial examination of the tubes and air testing suggested the possibility of fatigue cracks. Upon further and more detailed examination of the suspect tubes, it appears that the tube damage is not a result of fatigue failure. Rather, the nature of the indications associated with the air leakage tests suggests that brazing caused through wall leak paths. Although the braze and process has been changed since Module 1 fabrication, the plan is to inspect Modules 3 and 4 for similar indications. Evaluated Catalytic Module performance for W501D5 retrofit application. With unheated fuel, the inlet fuel-air mixture temperature is near previously measured PCI light-off temperature. Currently evaluating using higher air split to provide light-off margin and boost exit product temperature to near FD level.

Basket Development Completed full basket cost studies and preliminary evaluations. Catalytic Combustor costs appear competitive with Dry Low Nox and SCR under ATS application.

14.4 STEAM COOLED VANE TEST

No scheduled activity.