GE Power Systems

Utility Advanced Turbine Systems (ATS) Technology Readiness Testing

PHASE 3R

Technical Progress Report

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ACRONYMS USED IN GE ATS REPORT

ACC - active clearance control	DFSS - design for six sigma
AEC - Automated Eddy Current	DLN - dry low NO _x
ANSYS - <i>finite element software</i>	DOE - U.S. Department of Energy
APS - air plasma spray	DTA - differential thermal analysis
ATS - Advanced Turbine System	DTC - design to cost
AWS - aft wheel shaft	DVC - dense vertically cracked
CAC - cooling-air cooling	EA - Environmental Assessment
CAD - computer-aided design	EB - electron beam
CC - compressor case	EDM - electron discharge machine
CDC - compressor discharge case or casing	EDR - electronic data release
CDD - compressor discharge diffuser	EIS - Environmental Impact Statement
CFD - computational fluid dynamics	EPRI - Electric Power Research Institute
CMAS - calcium-magnesium-aluminum-silicate	FBD - Free Body Diagram
CMM - coordinate measuring machine	FCGR - fatigue crack growth rate
CNC - computer numeric control	FCP - fatigue crack propagation
CNRC - Canadian National Research Council	FCT - furnace cycle test
CRD - GE Corporate Research and Development	FEA - finite element analysis
CSMP - Coordination through Short Motion Programming	FEM - finite element model
CTP - critical-to-process	FETC - Federal Energy Technology Center
CTQ - critical-to-quality	FFT - Fast Fourier Transform
CVD - chemical vapor deposition	FMEA - failure modes effects analysis

FONSI - Finding of No Significant Impact	KCP - key control parameter
FPI - fluorescent penetrant inspection	KNP - key noise parameter
FPQ - first piece qualification	LCF - low cycle fatigue
FSFL - full speed, full load	LCVT - liquid crystal video thermography
FSNL - full speed, no load	LH - lower half
GASP - gravity-assisted shot peening	LUT - Laser Ultrasound
GEAE - GE Aircraft Engines	NACA – National Advisory Committee for Aeronautics
GEPG - GE Power Generation	NDE - nondestructive evaluation
GEPS - GE Power Systems	NDT - nondestructive testing
GTAW - gas tungsten arc weld	NEPA - National Environmental Policy Act
GTCC - gas turbine combined cycle	ORNL - Oak Ridge National Laboratory
HCF - high cycle fatigue	P&ID - process and interface drawing; process and instrumentation diagram
HIP - hot isostatically pressed	POD – Probability of Detection
HP - high-pressure	QDC - Quality Data Collection
HRSG - heat recovery steam generator	QFD - quality function deployment
HVOF - high velocity oxy-fuel	RAM - reliability, availability, and maintainability
IGCC - integrated gasification combined cycle	SEM - scanning electron microscopy
IGV - inlet guide vane	SLA – stereo lithography apparatus
IP - intermediate-pressure	SSPM - steady state performance model
IP&D - process and interface drawing; process and instrumentation drawing	SSRT - slow strain rate tensile STP - Segment Time Programming
IR - infrared	STEM – shaped tube electrolyte machining
IR - infrared	TBC - thermal barrier coating
IT - Inverse Time	TBO - time-between-outages
KCC - key control characteristic	

TC - thermocouple

TCP - Tool Center Point

TDM - thermal dynamic model

TDS - thermal dynamic simulation

TEM - transmission electron microscopy

TIG - tungsten inert gas

TMF - thermomechanical fatigue

TP - transition piece

UAB - Utility Advisory Board

UG - UniGraphics

UH - upper half

VGW - variable guide vane

VPS - vacuum plasma spray

VSV - variable stator vane

YFT - *fluids analysis software*

SECTION 1 EXECUTIVE SUMMARY

The overall objective of the Advanced Turbine System (ATS) Phase 3 Cooperative Agreement between GE and the U.S. Department of Energy (DOE) is the development of a highly efficient, environmentally superior, and cost-competitive utility ATS for base-load utility-scale power generation, the GE 7H (60 Hz) combined cycle power system, and related 9H (50 Hz) common technology. The major effort will be expended on detail design. Validation of critical components and technologies will be performed, including: hot gas path component testing, sub-scale compressor testing, steam purity test trials, and rotational heat transfer confirmation testing. Processes will be developed to support the manufacture of the first system, which was to have been sited and operated in Phase 4 but will now be sited and operated commercially by GE. This change has resulted from DOE's request to GE for deletion of Phase 4 in favor of a restructured Phase 3 (as Phase 3R) to include full speed, no load (FSNL) testing of the 7H gas turbine. Technology enhancements that are not required for the first machine design but will be critical for future ATS advances in performance, reliability, and costs will be initiated. Long-term tests of materials to confirm design life predictions will continue. A schematic of the GE H machine is shown in Figure 1-1. Note: Information specifically related to 9H production is presented for continuity in H program reporting, but lies outside the ATS program.

This report summarizes work accomplished in 2Q00. The most significant accomplishments are listed below:

7H – Specific

- Completed removal of gas turbine from the test cell, and transported it to the manufacturing area for post-test teardown and inspection
- Continued FSNL post-test data reduction and analysis
- Disassembled the unit rotor, and collected runout data
- Shipped rotors to the Houston, TX service shop for disassembly
- Continued full-scale 7H combustor development at ATS conditions to determine final configuration

9H/7H - Common Technology

- Continued work with suppliers to develop single crystal casting technology for large ATS gas turbine buckets and nozzles
- Initiated turbine rotor steam delivery rig test program

9H - Specific

- Continued final assembly operations for the 9H gas turbine in preparation for shipment to the commercial site

Figure 1-1. Schematic of the H gas turbine cross section

SECTION 2 TECHNICAL PROGRESS REPORTS: TASKS CURRENT IN THIS REPORTING PERIOD

SECTION 2.2 (GT) GAS TURBINE DESIGN

SECTION 2.2.2 (GTFF) GAS TURBINE FLANGE-TO-FLANGE DESIGN

Section 2.2.2.1 (GTFFCP) Compressor Design

Objective

The objective of this task is to design 7H and 9H compressor rotor and stator structures with the goal of achieving high efficiency at lower cost and greater durability by using proven GE Power Generation heavy-duty use design practices. The designs will be based on the GEAE CF6-80C2 compressor. Transient and steady-state thermomechanical stress analysis will be run to ensure compliance with GEPG life standards. Drawings will be prepared for forgings, castings, machining, and instrumentation for full speed, no load (FSNL) tests of the first unit on both 9H and 7H applications.

Progress for This Quarter

A tear down inspection was performed after the 7H FSNL test. The inspected compressor parts included all blades and vanes, inlet casing, compressor casing, compressor discharge casing, number 1 bearings, all VSV assemblies, and the entire rotor shaft and wheel assembly. The results indicated all parts met their design intent except for some tip rubs in the front stage blades, and some wear marks in the S17 slot that were observed during the tear down.

In order to avoid the tip rubs, the tip configurations of all front stages from R0 to R3 have been redesigned. The affected blades will be re-worked in the third quarter and be evaluated during the next FSFL pre-shipment.

The wear marks in the S17 slot were caused by the rigid body motion of S17 vanes. A new segment S17 design was introduced to address this issue. The affected vanes will be re-worked into segmented assemblies in the third quarter and be evaluated during the next FSFL pre-shipment test.

The 7H FSNL test was conducted from January 24 to February 11. A post test review was held on March 14 to review the test results and the gas turbine is in the tear-down process for the post-test inspection test.

Plans for Next Quarter

The plan for next quarter will focus on 1) the hardware re-work for the front stage blade tips and for the segmented S17 vanes, and 2) re-assembly of the compressor in preparation for the next FSFL pre-shipment test.

Technology Application

The compressor design (aerodynamic and mechanical) and rig test results establish the basis for the 7H and 9H compressor production hardware.

Section 2.2.2.2 (GTFFCB) Combustor Design

Objective

The objective of this task is to design and develop a combustor based on the commercial DLN-2 combustion system, with modifications made for improved use of available air, reduced cooling, and greater load turndown capability. This design will be similar for both the 7H and 9H machines. It will be configured to ensure the ability to use preheated fuel. Rig testing of full-scale and scaled components will be conducted at 7H and 9H cycle conditions. The final configuration will be validated in single-combustor, full-scale tests under full operating conditions.

The premixer-burner design will be optimized to use minimum pressure drop, achieve required fuel/air mixing, maintain stable flame, and resist flashback. The basic design will be developed and evaluated in full-scale single burner tests and then implemented in full-scale combustors. The ability to meet high cycle fatigue (HCF) life goals depends on understanding the effects and interrelationships of all combustion parameters. Existing dynamics models used in parallel with laboratory-scale and full-scale testing will be used to predict combustor dynamic behavior.

Chamber arrangement, casings, cap and liner assemblies, flame detectors, and spark plugs will be designed and analyzed to ensure adequate cooling, mechanical life, and aerodynamic performance. Fuel nozzles will be designed for operation on gas alone or on gas with distillate as a backup fuel. The transition piece will be designed and integrated with the design of the machine mid-section, transition duct cooling, and mounting.

Progress for This Quarter

Further mapping tests of the four nozzle chamber configuration were put on hold pending delivery of a set of fuel nozzles with fuel injection holes sized to accommodate moisturized fuel.

Final deliveries of all hardware for the 9H production checkout test were received.

Plans for Next Quarter

The 9H production checkout test will be performed. GEAE Test Stand A2 will then be configured to enable heated fuel moisturization. The 7H production checkout test will then be run with moisturized fuel late in the quarter or early fourth quarter.

Technology Application

Design and development of the combustion system is required for the ATS gas turbine to meet the low emissions targets at the high cycle conditions of inlet temperature, pressure, air flow, and outlet temperature, all of which are greater than those of any of GE's developed products.

Section 2.2.2.3 (GTFFTR) Turbine Rotor Design

Objective

The objective of this task is the design of turbine rotor components (wheels, spacers, aft shaft, transition discs, coolant systems, and fastening devices). Transient and steady-state stress analyses will be used to calculate parts lives. Rotor and system vibratory characteristics will be evaluated. The coolant flow circuit for routing the cooling steam to and from buckets will be designed and performance calculated. Test results will be incorporated concurrently. Drawings and specifications will be developed in preparation for manufacturing.

A modified 7F turbine rotor will be fitted with production steam delivery hardware, and run to simulate full-scale 7H and 9H centrifugal loading and transient thermal interactions between steam delivery hardware and rotor wheels. Testing will accumulate start/stop cycles on the steam delivery hardware, measure movement of the axial tubes, determine wear characteristics between hardware with and without dry film lube, observe spoolie wear due to cyclic operation, and measure changes in steam leakage over time due to cyclic operation.

Progress for This Quarter

The 9H and 7H thermal models have been updated based on the results from the 9H FSFL pre-shipment and 7H FSFL pre-shipment testing. In this updating process, the 9H marriage flange D nuts were determined to produce excessive thermal heating due to windage. The nuts were redesigned to greatly reduce its windage.

Gravity sag analyses were conducted in conjunction with rotor/casing alignment. Using laser alignment procedures, the rotor sag models for both the 9H and the 7H rotors were accurately verified and the alignment to the casing was fine tuned for future assemblies.

Rotor lifing is continuing with efforts to automate the process. This includes developing scripts and software packages to streamline the process.

The 7H FSNL rotor was disassembled in preparation for instrumentation of the rotor for FSFL pre-shipment and FSFL testing. Accurate heat transfer models were used to help in the disassembly process. The robust design of the rotor rabbets needed sophisticated methods to determine when the mating components reached optimum thermal conditions for piece part removal.

Plans for Next Quarter

Data reduction from the 9H FSFL pre-shipment test and 7H FSNL tests will continue next quarter, and analysis models will be exercised to understand any differences from pre-test predictions. Once complete, the models will be updated where necessary, or, in some cases, hardware changes will be recommended to optimize rotor performance.

This initial analysis will be followed by running the rotor system analysis models to simulate the various operational variations the units will see in service in order to establish the lives of components and robustness of the systems.

Component robustness studies on some components will also commence to determine the performance of components to variations in the design parameters.

Turbine Rotor Rig

All testing of the steam delivery testing in the rotating rig has been completed. The goal was to run 140 cycles on the hardware to simulate the first run of the 9H rotor. The total cycle count at the completion of testing was 201 cycles, thus providing a healthy margin.

Many modifications were made to the wheelbox facility to achieve this number of cycles. Wheelbox overheating (due to windage heating) was controlled by testing the rotor in a vacuum, as well as supplying cooling air to vital components and instrumentation. The temperature in the wheelbox was kept below 180F throughout testing.

Failures of the electromagnetic clutch were also of concern during testing. This issue was dealt with by installing monitoring instrumentation and feedback loops to the clutch. The monitoring included bearing temperature, cooling water temp, cooling water pressure, cooling water flow, water detection in bearing cavity, vibrations and current usage. The clutch performed flawlessly throughout the remainder of the testing.

Another area of concern was rotor dynamics. Once the wheelbox temperature was reduced, the dynamic response of rotor came back to within predicted limits. Occasionally during testing, the rotor rig was shut down due to facility problems. These 'hot' shut downs gave us a slight bow in the rotor. In all cases we were able to restart the rotor slowly and keep the vibes below limits.

Throughout the testing there were never any problems with the steam delivery hardware. Stresses and vibrations stayed well within limits. The movement of the steam delivery hardware due to thermal ratcheting behaved as predicted. Pre and post test leakage measurements were made, and no appreciable change in leakage could be seen. In all, the test was successful.

Plans for Next Quarter

Modifications to the analytical models will continue, and the models will be compared to the test data to improve the model predictions. Data reduction from the FSNL tests will also continue during the next quarter.

The rotor system analysis models will be run to simulate variations the units will see in operational service in order to establish the lives of components and robustness of the systems.

Component robustness studies will be initiated on some components to determine the component performance changes to variations in the design parameters.

Turbine Rotor Rig

Turbine rotor rig testing has been completed.

Technology Application

The turbine rotor analysis and design effort defined the basis for the 7H and 9H production hardware.

Section 2.2.2.3.5 (GTFFTB) Bucket Temperature Monitoring

Objective

The objective of this task is to provide the steam-cooled rotor buckets with protection against a loss-of-steam-coolant event. The protection system will provide a timely signal enabling the turbine to be shut down with minimal damage.

Progress for This Quarter

No activity this quarter.

Plans for Next Quarter

Control algorithms will be evaluated using 9H FSFL pre-shipment and 7F TBC field data.

Technology Application

Pyrometers will be used in the ATS gas turbine to monitor steam-cooled turbine blade temperature during operation. This will allow for timely detection of insufficient steam coolant flow into the buckets.

Several other technologies were investigated, such as tracer leaks, vibrational signatures, steam pressures, and steam flowrates, but they were discarded in favor of monitoring the bucket temperatures using pyrometers attached to the outer casing of the turbine with a direct line-of-sight view of the first- and second-stage buckets. Pyrometers have several significant advantages: (1) they respond to the parameter of the buckets that is of most concern, i.e., the temperatures; (2) all

the buckets in a stage come into the field of view of a single fixed pyrometer; and (3) the detection system has a rapid response time.

Section 2.2.2.3.6 (GTFFTR) Rotor Component Flow Tests

Objective

The objectives of this task are (1) to experimentally determine loss coefficients vs. Reynolds number for selected components in the rotational steam cooling path; (2) to identify high loss areas for each of these components; and (3) to provide loss data for verifying YFT and CFD models.

Design codes like YFT require that a loss coefficient be input for each node (e.g., elbows, tees, and manifolds) of the flow circuit. Flow handbooks and reports provide loss coefficients for typical plumbing fixtures used in steam path plumbing, but much of the steam circuit contains non-standard nodes for which loss coefficients are not available. This task identifies those non-standard nodes and develops the required loss coefficient data. To provide the data models for each of the non-standard nodes, airflow tests at near atmospheric conditions will be conducted to establish the loss coefficient vs. the Reynolds number for that node. The data from the atmospheric test will then be used to benchmark a CFD code that will calculate the loss coefficient in steam at gas turbine pressure and temperature and with rotation. The CFD work is reported in Section 2.2.2.3.3.

Progress for This Quarter

No flow testing work was required this quarter, 3D CFD analysis will be used to determine the flow characteristics of the new rotor steam bore tube inlet design due to the successful correlation of CFD to test results proven earlier in this program.

Plans for Next Quarter

No further work is planned.

Technology Application

The results of this task helped validate the use of analytical tools such as CFD and YFT for the design of the rotor steam circuit components. In addition, data from these tests was used to make performance-related design decisions.

Section 2.2.2.4 (GTFFTB) Turbine Bucket Design

Objective

The objective of this task is the design of buckets for the four rotating stages. The heat transfer and material databases for steam-cooled first- and second-stage buckets continue to expand and will be integrated concurrently with the design. Cooling passages will be sized consistent with manufacturing practicalities and the bucket life requirements. Flow variation and consistency will affect life calculations and will be considered. Current practices for thermomechanical steady-state and

transient analyses, dynamics and vibration analysis (which can deal with anisotropy), and corrosion/oxidation analysis will apply throughout. Drawings and specifications will be developed in preparation for manufacturing.

Progress for This Quarter

The external profile definition of the 7H Stage 1 bucket shank was released at the end of the quarter after solutions were found to mitigate aeromechanical interaction with upstream nozzle passing frequencies. Solutions were found which did not necessitate further changes to the core die.

The stage 2 bucket second torsion mode also crosses with upstream nozzle synchronous (vane passing) wakes with little margin. The airfoil external definition was re-shaped to improve design margins and the external airfoil shape redesign was released in the second quarter. Construction of the core die was completed at the end of the quarter. Casting tooling core and pattern dies were delivered for the third and fourth stage buckets. Casting trials were initiated on the stage 3 and 4 buckets.

Plans for Next Quarter

The 7H Stage 1 and stage 2 bucket casting trials will take place in the third quarter to establish the metallurgical process at the casting vendor. The stage 3 and 4 casting trials will continue to progress into First Piece Qualification. Design work will continue to detail the casting and machining drawings and to finalize the platform film cooling designs of the stages 1 and 2 buckets.

Technology Application

The design and development of turbine buckets are required for the ATS turbine to ensure that the buckets deliver power to the turbine shaft and that they meet the stated part life requirements.

Section 2.2.2.4.3.2 (GTFFTB) S1B Forced Response Analysis

Objective

Although current analysis techniques do not customarily predict the forced response of turbine airfoils from a first principles basis, the ability to carry out such an analysis would have design and development benefits. The objective of this task is to develop an engineering approach to predicting the forced response of stage 1 buckets to the excitation due to stage 1 nozzle passing frequencies. Three bucket modes are of specific interest. The resulting analysis will be applied to both Full Speed, No-Load and Full Speed, Full-Load operating conditions.

Progress for This Quarter

An 84 order aeromechanical response of the S1B was observed during the 9H FSFL pre-shipment tests. Although only 30% of engineering limits, at 100 % FSFL pre-shipment test conditions, the question arises as to what the response would be at FSFL test conditions. Three potential mechanisms were identified: 2x S1N count, 1x S1 shroud count and 6x combustor count.

The first mechanism of excitation considered in this analysis was 2x-nozzle-count. Numerical difficulties prevented an adequately converged viscous CFD solution from being attained for the flow in the stage 1 bucket. Since experience has shown that without a fully converged solution for the steady bucket flow, an unsteady flow solution cannot be defined, the decision was made to use an inviscid analysis for the bucket. The nozzle flow solution, which provides the unsteady stimulus for the bucket, was still calculated with fully viscous analysis. Total modal damping for the bucket response observed in the FSFL pre-shipment test was estimated from experimental data. Aerodynamic damping levels were calculated using the CFD code and found to be small in comparison to the total damping value. As a result, it was possible to assume that the damping factor for the FSFL response was the same as that observed for FSFL pre-shipment test conditions.

The bucket frequency of most concern is described as the first 3-stripe mode and is excited at the operating speed of the machine. Using this modal response, the unsteady flow solution derived from the CFD analysis and the experimentally estimated damping factor, the forced response of the S1B at FSFL pre-shipment test conditions was calculated and compared to measured strain response from the FSFL pre-shipment tests. The response predicted by the CFD analysis was found to be 1/13 of the mean value of the measured bucket response in the FSFL pre-shipment test. A similar prediction was made to determine the expected response at FSFL conditions. Although the response was predicted to be 3.8 times higher at the FSFL test conditions, the large discrepancy between prediction and observed response at FSFL pre-shipment conditions has led to the conclusion that there is not enough evidence to believe that the 2x-nozzle-count excitation is driving the observed S1B response.

A CFD based analytical procedure was also devised to assess the possibility of excitation due to 1x-shroud count excitation. The assumption behind this driving mechanism is that the shroud shape will deviate from a perfect cylinder, especially at FSFL pre-shipment operating conditions. Based on measurements of the non-circularity of the shrouds at FSFL pre-shipment conditions, the analysis predicts a modal response of the S1B at FSFL pre-shipment conditions which is 50% to 63% of the mean measured response of the bucket. Although the analysis is not standard, this prediction is much closer to the observed response. The expected response at FSFL due to this excitation is predicted to be smaller for two reasons. First, for the same deviation from circularity, the CFD analysis predicts that the response at FSFL would be lower. Second, at FSFL conditions, the deviation of the shroud shape from circularity is also less, and as a result the response is also diminished.

Plans for Next Quarter

This task has been completed.

Technology Application

A successful methodology of predicting forced response of turbine buckets will allow a priori prediction of response at arbitrary machine operating conditions and provide an engineering tool for

risk assessment. Comparison of these analysis results with test results from full speed, no-load conditions will be used to assess the accuracy of this prediction and suggest future improvements.

Section 2.2.2.4.5.1 (GTFFTB) Loss of Steam Cooling Algorithms for Full Load Operation

Objective

Loss of steam cooling would be a critical event that needs to be monitored and acted upon within the control logic of a steam cooled gas turbine. Appropriate control logic to rapidly detect cooling leaks above a threshold level was developed and demonstrated for air cooled operation of the steam delivery system during the Full Speed No-Load tests. The objective of this task is to evolve this control logic to maturity for steam-cooled full-load conditions and complete the final code algorithms.

Progress for This Quarter

Four previously developed algorithms for controlling a loss of steam event were originally assessed during FSNL testing. Two of the algorithms offer detection plus fault isolation and were designed to handle transients between operating points. The remaining two algorithms were intended to be simple and easily understood by an operator. The plan was to eventually down-select to two algorithms. An algorithm-handling transient between operating points has been selected. Results during FSNL testing indicated that the two original simple algorithms did not work effectively during operating point transitions. As a result, there was a need to revise one of these simple algorithms to incorporate an additional system dynamic model accounting for transients. The revisions required for this second backup algorithm have been defined. Controls and Accessory Systems Engineering will code this algorithm. A Chief Engineer's Review has been rescheduled for late August. Options for calibrating the model parameters within the algorithm have been defined and proposed. The algorithms are being prepared to run with a simulator in order to test algorithm performance under expected FSFL operating characteristics.

Plans for Next Quarter

The algorithms will be run on the simulator for performance assessment. A parameter calibration concept will be selected and a calibration procedure will be documented.

Technology Application

The control algorithms developed in this task will be validated at full-speed full-load conditions and used as part of the control system for the commercial product.

Section 2.2.2.4.7 (GTETIH) Bucket Platform Cooling Model Validation

Objective

The objective of this task is the quantification of the first- and second-stage platform cooling design, including the principal features of impingement onto a roughened surface, film extraction, and shank leakage. A scaled liquid crystal test model will be designed to investigate effects of parameter ranges of the first-stage bucket, with built-in variability for the most important features. Gas turbine roughness levels will be compared to smooth surface tests. Improvements to the present design will be tested if needed. CFD modeling will also be performed to incorporate the effects of rotation.

Progress for This Quarter

Experimental efforts in 4Q99 were on hold pending the completion of the improved platform cooling design. No test section modification or testing took place.

Plans for Next Quarter

Design Engineering will select a revised platform cooling design so that work can begin on the modification of the existing model test section in preparation for validation testing.

Technology Application

Because of the higher firing temperatures of the ATS turbine and the relatively flat radial temperature profiles experienced by large power turbines, bucket platform cooling requires more attention than in previous turbines. Specifically, the first- and second-stage bucket platforms require active cooling to assure component design life. The detailed local heat transfer coefficients measured in this model test, along with the variation of key cooling parameters, will be used to provide the most robust platform cooling with optimization of coolant usage.

Section 2.2.2.5 (GTFFTS) Turbine Stator Design

Objective

The inner and outer turbine shells will be designed, including a turbine stator cooling system to provide rotor/stator clearance control. A closed circuit coolant delivery and return system for the turbine flowpath stator components will be designed. Component, sub-assembly, and assembly flow tests will be incorporated concurrently. Implications for handling equipment (crane and manipulators) will be included in design considerations.

Steam-cooled turbine nozzles will be designed. Thermomechanical transient and steady-state analyses will be run to determine parts lives. Material, manufacturing, and heat transfer database expansion is planned and will be integrated concurrently.

Shrouds will be designed. Sealing systems will be selected for minimum leakage. Thermal and structural analyses of equiaxed or anisotropic materials will be applied as appropriate.

Calculations will be made of all flow in the cooling systems, including leakage flows, to support performance, thrust balance, and component temperature calculations.

Design of hot gas path seals will be based on laboratory tests. Seals developed for transition-piece-to-nozzle-segment and intersegment interfaces will be evaluated in cascade tests. Both sealing and wear performance will be assessed. Manufacturing drawings and specifications will be produced.

Progress for This Quarter

7H Stage 1 Nozzle

Progress was made on the design and manufacture of the first set of 7H stage 1 nozzle hardware. The casting development cycle is progressing, and development castings were successfully produced. The production casting tooling was completed, and casting trials using the production tooling are in progress. Cooling circuit and structural analysis are in process to support the release of the production fabrication details. Casting releases have been completed on the main airfoil and related nozzle hardware.

9H Stage 1 Nozzle

The 9H stage 1 nozzle has made progress in two areas during the first quarter of 2000. The nozzles for the first FSFL test were completed through the majority of the fabrication cycle, and have begun the assembly cycle into the inner turbine shell. The nozzles have extensive instrumentation that is being led out of the inner turbine shell assembly and will be monitored during FSFL testing. The instrumentation will provide important feedback to the design and manufacture of subsequent hardware.

The design of the second set of hardware is also progressing. Cooling circuit and structural analysis is in process to support the release of the production fabrication details. Casting releases have been completed on the main airfoil and related nozzle hardware.

9H Stage 2 Nozzle

The assembly of the 9H FSFL second stage nozzle has been completed on the lower half assembly of the inner turbine shell. The upper shell was completed, short one segment, due to needed rework on the TBC. Completion is expected very early in the third quarter. Several pressure checks were completed on the assembled nozzles and steam feed piping that verified the integrity of the steam cooling circuit. Prototype instrumentation was led out through the inner shell and readied for final assembly within the unit.

The second set of hardware is progressing well with the final casting trials heading towards completion and First Piece Qualification (FPQ) of production hardware coming closer. Post cast operations are being developed and tested for attachment and fabrication of the other assembly parts. Cooling flows of both air and steam circuits are being developed to validate design life and

meet system requirements. System requirements and interfaces with other hardware have driven design improvements for the inner side wall to diaphragm connections.

Plans for Next Quarter

Steam-cooled 7H Stage 1 Nozzle

Progress will continue on both the design and manufacture of the first set of development nozzles.

The casting development process will continue for the first set of hardware. Design release details for the internal nozzle assembly will be completed, along with top level fabrication and machining definition. The manufacturing development process will continue with joining, machining, and TBC trials planned. The design process will continue in support of the definition release and will include reviews to ensure compliance with internal GE design criteria and program requirements.

9H Stage 1 Nozzle

Progress will continue on both the manufacture and assembly of the first set of development nozzles and design of follow-on hardware.

Final assembly work on the nozzle FSFL development hardware will be completed, and the inner turbine shell will be prepared for shipment and installation into the FSFL test engine. The installation will include the lead out of all the prototype instrumentation.

The casting development process will be started for the second set of hardware. Design release details for the internal nozzle assembly will be completed along with top level fabrication and machining definition. The manufacturing development process will continue with joining, machining, and TBC trials planned. The design process will continue in support of the definition release, and will include reviews to ensure compliance with internal GE design criteria and program requirements.

9H Stage 2 Nozzle

Final assembly of the FSFL hardware will be completed and assembly into the surrounding turbine shell support structure will be started. Instrumentation lead out will be worked through the outer turbine shell assembly.

The casting development process will be completed and the initial casting production lot will be started. The manufacturing development process will continue with joining, machining and TBC trials planned. Preliminary assembly of several full life design segments will be started in order to gain experience on the assembly and fabrication processes before production hardware is available. The design process will continue in support of the definition release, and will include several reviews to ensure compliance with internal GE design criteria and program requirements.

Technology Application

The turbine stator analysis and design effort defined the basis for the 7H and 9H production hardware.

Section 2.2.2.5.2 (GTFFTSTSTIS) Brazed Microturbulator Manufacturing Process Development**Objective**

One approach to enhancing heat transfer in the internal steam cooled passages of nozzles and buckets is through the use of microturbulators which are brazed onto the internal walls of the airfoils. The objective of this task is to develop the manufacturing processes for applying these microturbulators. This includes development of the braze chemistry and process parameters to produce adequate microturbulator life.

Progress for This Quarter

Three braze chemistry trials were performed, first on Hast-X parts and then on single crystal N5 material. The braze chemistry has been identified for use in the H stage 1 nozzle process window for microturbulator application in all orientations (horizontal, vertical, and inverted). Bend testing has been performed which shows brazed microturbulator cracking in specimens with 5 mil braze layers. Specimens were then fabricated to evaluate life and tensile adhesion for thin and thick braze layers.

Plans for Next Quarter

Additional life testing and risk reduction will be carried out as required. Process will be defined and documented.

Technology Application

This process will enhance heat transfer and cooling and extend the life of hot gas path hardware.

Section 2.2.2.6 (GTFFST) Structures Design**Objective**

The objective of this task is to design the exhaust frame and diffusers, steam gland, and aft bearing housing. Instrumentation and test plans for component model, factory, and field testing will be prepared.

Progress for This Quarter**9H/7H Compressor (& Hot) Structures**

7H unit disassembly was completed with removal of the rotor and gas path components. FSNL post-test data reduction continued, with many pretest predictions being verified and root cause analysis initiated where data showed differences to prediction. All pretest CTQs were successfully achieved during the test program.

Additional 7H stator tube inspections using SMX laser technology were made to help understand the unit rotor gravity sag. Correlation of laser inspection data with the rotor sag measurements for optimization of cold and hot alignment/clearances has been initiated. Similar work on alignment was completed on the 9H unit. The final 9H FSFL test engine alignment, which will include a No.1 journal bearing change-out with the rotor to optimize clearances, was also completed.

Steam gland honeycomb and brush seal testing in air and steam was completed at CRD. The 9H seal drawings were issued, and final flow circuit definition was documented to the current flow extraction pressures. The 9H FSFL test engine steam gland was re-worked at a vendor for some seal changes, and for additional instrumentation. Work continued on analysis of the interaction between the steam pipes and their flows as part of the overall power plant system.

Plans for Next Quarter

The 9H FSFL test engine re-assembly will be completed utilizing the final alignment definition.

The 7H inner turbine shell re-assembly with instrumented and production hot flowpath hardware will be completed. A ping test of the stator steam piping for modal analysis validation will be completed on final assembly. The instrumented rotor installation will be completed.

Final system issues will be resolved for the 9H FSFL test gas turbine hardware interfaces. Work will continue on the 7H gas turbine steam seal and clearance definition to allow final design release.

Technology Application

This analysis and design effort establishes the basis for 9H and 7H structure designs.

Section 2.2.2.7 (GTFFMS) Mechanical System Design

Objective

The objective of this task is to perform system level studies to optimize cost and performance. Performance, cost, weight, and other system level integration issues will be monitored and tracked. A flange-to-flange cross-section drawing will be maintained, and all mechanical interfaces will be controlled. All gas turbine systems, as well as the technical requirements for accessories, will be defined and specified.

Progress for This Quarter

The focus of work was the 7H disassembly and inspection after the FSNL test, and the preparation of the 9H for the shipment.

The 7H Gas Turbine full speed, no load (FSNL) test was completed in 1Q00, and the unit shipped back to Assembly for teardown and inspection. Inspections of the unit and rotor indicated no unexpected anomalies. The unit has been placed in long term storage, waiting for turbine airfoils to complete manufacturing. The rotors have been shipped to the gas turbine service shop in Houston, TX to remove the FSNL airfoils and complete machining of the turbine rotor.

The 9H shipment preparations continued, as additional hardware is being installed to support the FSFL characterization test.

Development of supporting technology that benefits both the 9H and 7H turbines continued.

Plans for Next Quarter

Ship the 9H to the project site, continue 7H turbine airfoil manufacturing, and start 7H rotor final machining.

Technology Application

The cross-functional systems review team will ensure that field experience lessons learned are incorporated into the component designs, thus optimizing performance, cost, weight, size, maintainability, reliability, and manufacturability.

Section 2.2.2.8 (GTFFPP) On-Base and External Piping Design

Objective

The objective of this task is to design piping for fuel, air, steam, water, and oil transfer. A turbine base will also be designed for securing the ATS gas turbine to the foundation.

Progress for This Quarter

The data collected during the 9H FSFL pre-shipment test were analyzed and are being fed back into the on-base designs. This data will be used to improve the 9H unit as planned for first Customer shipment as well as being used to improve the 7H unit. Work continues to finalize the documentation package for the 9H unit that will ship to the field later this year.

The first 7H FSNL test was a success for the hardware covered in this section. The data collected during this 7H FSNL test are being analyzed and will be fed back into the on-base designs. This data will be used to improve the 7H as well as the 9H unit.

Plans for Next Quarter

Incorporation of the 9H FSFL pre-shipment lessons learned into the final product will continue. The documentation release of all hardware required for a field installed unit will be completed. Work will continue on the documentation package for the 9H unit which will ship to the customer site later this year.

Incorporation of the 7H FSFL lessons learned into the product will continue. The documentation release of all hardware required for a second FSFL pre-shipment test and toward a field installed unit will continue.

Technology Application

The turbine base and piping designs require the consideration of new ideas in this technology application. The turbine base must be capable of handling and transferring much larger loads than in previous gas turbine designs. This requirement is complicated by the limited space available to the turbine base because of the machine shipping envelope, the increased number of systems requiring piping for fluid transport, the piping size and quantity, and the foundation interface limits. In summary, the piping design challenge is driven by the increase in size and quantity of fluid systems support required by the turbine and the limited space around it.

Section 2.2.2.9 (GTFFIT) Instrumentation and Test

Objective

The objective of this task is to instrument and conduct field tests that validate the ATS gas turbine design for mechanical integrity, operating performance of the unit, and establish emissions performance. Test plans will be formulated and instrumentation will be specified. Compressor and turbine rotor telemetry systems will be developed and acquired.

Progress for This Quarter

The 7H FSFL test program was completed during 1Q00. The 7H (FSFL test) unit was removed from test cell and transported to the assembly area, where the casings are disassembled. The rotor was removed from the half shell and inspected. The rotor was disassembled, reworked and instrumented. The casing tube is in storage. Next phase is the unit assembly with instrumented turbine components and minor compressor rotor modifications.

After 9H FSFL pre-shipment test (in 4Q99), the 9H unit was disassembled and inspected. The 9H unit rebuilding is in process. The casings were realigned. The rotor modifications were completed, other than bore tube assembly. The turbine inner shell and nozzles are assembled at Houston service shop including new first & second stage turbine nozzles, shrouds and steam tubes.

Work continues on the 9H FSFL test plan, with definition of the test CTQ's.

Plans for Next Quarter

The 9H unit rebuild will continue with installation of new first and second stage turbine nozzles, shrouds, inner turbine shell, and rotor bore tube.

Technology Application

These are test plans to establish the instrumentation requirements for 7H and 9H FSNL, FSFL pre-shipment, and FSFL test.

SECTION 2.2.3 (GTET) TECHNOLOGY VALIDATION

Objective

The overall objective of this task is to provide confirmation of critical component design and technology. The validations include hot gas path component testing, sub-scale compressor testing, steam purity test trials, and rotational heat transfer testing. Technology enhancements that are not required for the first machine design but will be critical for future ATS advances in performance, reliability, and costs will be conducted.

Section 2.2.3.5 (GTETIH) Surface Enhanced Internal Heat Transfer

Section 2.2.3.5.11 (GTETIH) S1N and S2N Cooling Circuit Flow Tests

Objective

The cooling flow circuits of the first- and second-stage nozzles and buckets of the ATS gas turbine have complicated flow configurations. The first- and second-stage nozzles have several impingement-cooled flow cavities connected in series and in parallel depending on the design requirements. Design flow models involve several empirical friction factors and flow element head loss coefficients that were taken from the best knowledge available. The models need experimental verification with typical cast components.

The objective of the flow checks, conducted with air, is to check the flowrates and static pressure distributions of typical cast first- and second-stage nozzle components. These tests are necessary for the production nozzle (first- and second-stage nozzle) as well as the nozzles that will be used in the GEAE Evendale cascade tests. The results will be compared with the design flow model predictions. The measured overall coolant flowrates for a given overall inlet-to-exit pressure ratio will also form the basis for future quality flow tests to ensure that every component fulfills the flow design requirements.

Progress for This Quarter

With the first-stage nozzle cavity 1, 5, and 6 inserts in place, the flow distributions through the outer side wall impingement plate were investigated. Five series of tests were conducted to evaluate the assumptions made for the outer side wall impingement hole patterns and the flow distributions expected through these cavities. The test results showed that the stagnation line was well predicted and the flow distributions were close to expectations.

Flow tests were conducted, with and without the inlet metering plates, for a set of six airfoil impingement cavity inserts.

An overall flow test at the design pressure ratio was conducted on a first-stage nozzle casting received from GEPS. The measured flow was found to be just a few percent higher than the upper specification limit.

Plans for Next Quarter

Component and assembly cooling circuit flow tests will continue for production quality castings and inserts as they become available.

Technology Application

The flow and static pressure distributions results obtained with the cast components were used to check the design flow model predictions and ensure that the predictions were correct and that there were no regions that have friction and head loss factors different from the design assumptions.

The flow and static pressure distributions results obtained with the Evendale test cast components will check the design flow model predictions, generate flow data that can be used in subsequent modeling, and ensure that the flow characteristics are well characterized.

Section 2.2.3.5.12 (GTETIH) Nozzle Fillet Heat Transfer

Objective

The objective of this task is to determine impingement heat transfer behavior in the fillet regions of the first-stage nozzle. There are two internal fillet regions in the first-stage nozzle design: (1) the spanwise cavity rib fillets subjected to airfoil insert impingement and (2) the fillets at the endwall perimeter edges, which represent the furthest extent of impingement into corners. Because thermal gradients make these fillet regions critical lifing areas, detailed heat transfer coefficients are required. A liquid crystal cooling model test will be designed to determine heat transfer distributions with various geometries.

Progress for This Quarter

As reported in the Annual Report, detailed internal heat transfer coefficient distributions for two geometries of endwall fillet – or turning region – cooling were determined. These data were transmitted to Design Engineering with appropriate scaling information for application to the first-stage nozzle as thermal boundary conditions.

During the present reporting period, no activity has taken place to extend this effort to revised geometries, pending the completion of improved regional designs and associated design optimization studies.

Plans for Next Quarter

Design Engineering will complete their evaluation of improved or re-designed regions, at which juncture one or more models will be designed for validation testing, fabricated, and then tested. The

validation and optimization testing of such fillet regions of the first-stage nozzle may also be extended to other internally cooled features of the nozzle design.

Rig test preparations will be initiated, with testing planned for 2Q00. The rig will incorporate the new design for enhanced nozzle fillet and endwall heat transfer.

Technology Application

The first-stage nozzle endwall edge regions represent the furthest extent of impingement cooling within the steam circuit of the nozzle. These edge regions must balance the local cooling requirements with those of more inboard regions that experience cross-flow effects from the edge flow. The other fillet regions of the nozzle represent areas of casting orientation changes, TBC structural variations, in-plane thermal gradients, and stress concentrations, and so require more detailed knowledge of the local heat transfer conditions. The liquid crystal test models will provide detailed heat transfer coefficient distributions for such specific geometries of the airfoil and endwalls. These data will be used to confirm design and component lifing. The models will provide vehicles to further optimize this cooling as required.

Section 2.2.3.5.14 (GTETIH) Production Stage 1 Nozzle Cooling Circuit Flow Checks

Objective

The H machine stage 1 nozzle is a steam cooled component significantly different in thermal design than air cooled nozzles. The objective of this task is to conduct flow checks of the stage1 nozzle components which will be tested in the cascade tests to be carried out at Evendale later this year.

Progress for This Quarter

Leaks in the previously tested nozzles were repaired and they were returned for additional flow testing. As in the first set of tests, all the impingement holes were open and the flow through cavity 1 only, flow through cavities 6 and 7 together, and flow through all cavities were quantified. Leaks were identified between passages 1 and 2, although the leaking flow was much lower than previously measured. Leaks were quantified and reported to engineering.

Plans for Next Quarter

Flow checks will be carried out as necessary for engineering.

Technology Application

Flow checks of these components will be compared with analytic predictions to validate design models. The data will also provide information on statistical scatter of nozzles due to manufacturing tolerances.

SECTION 2.2.4 (GTMT) MATERIALS TECHNOLOGIES

Section 2.2.4.1 (GTMTSE) Steam Effects on Mechanical Properties

Objective

The objective of this task is to evaluate the candidate turbine materials for any effects due to operation in a steam environment. Tests of materials that are exposed to steam will be performed to measure fatigue crack propagation, low cycle fatigue, and creep. Additional tests deemed necessary to meet design criteria will be performed. Comparisons will be made to data collected in air. Where necessary, the program will evaluate the roles of alternate heat treatments and/or surface treatments.

Progress for This Quarter

Creep and Rupture Tests in air were performed on wrought IN718. Fourteen (14) of fifteen (15) planned tests for forging from Ingot #3 were completed. The remaining test now running at 1000F and 115 ksi has accumulated 37,870 hours. Also Thirteen (13) of fifteen (15) planned tests for forging from ingot #4 were completed. Two tests are in progress. The first at 900F/145 ksi has accumulated 28,312 hrs, and the second at 1000F/110 ksi has accumulated 26,707 hours.

Plans for Next Quarter

Continuation of creep tests to at least 70,000 hours. This will ensure the confidence of long lifetime extrapolation of creep and rupture curves. Also planned are the following:

Hold Time Effect in FCGR - The steam and partial steam environment data assembled will be used during the first half of the year 2000 to generate an estimate of the effect of 50% steam on IN718 crack growth.

Hold Time Effect in LCF - The limited available in steam environment LCF and crack growth data will be used during the first half of the year 2000 to generate estimates of the hold time LCF behavior of forged IN718 in steam.

Technology Application

This task will evaluate the behavior of turbine materials in a steam environment in order to account for introduction of steam cooling.

Section 2.2.4.10 (GTMTTA) Turbine Airfoils Materials and Processes

Objective

Microstructure and mechanical properties will be evaluated for full-sized castings processed in this program. A comprehensive program will yield final specifications with appropriate heat treatments and will quantify the effects of ATS airfoil geometry and structure/property variability. Casting processes will be developed for all airfoils by utilizing developmental casting trials. Critical nozzle

and bucket long-term material properties will be measured at elevated temperatures. Metallic coating systems will be developed for internal and external oxidation protection of the airfoils. Samples will be coated using various techniques for optimization studies and process verification.

Progress for This Quarter

LCF tests on material welded with an alternative joining process simulating airfoil joints were completed. Knockdown factors for design were developed using the data generated.

Plans for Next Quarter

No future work planned for this activity.

Technology Application

This task will enhance the database of mechanical properties at service conditions for bucket, nozzle, and shroud materials.

Section 2.2.4.14.3 (GTETBS) 7H Stage 3 Nozzle Brush Seals

Objective

Preliminary analysis indicates that the application of brush seals to the third stage diaphragm of the 7H gas turbine would improve turbine efficiency and heat rate and, as a consequence, increase both combined cycle efficiency and power. The objective of this task is to carry out the necessary development work to define the design that will be most effective for the third stage diaphragm of the 7H gas turbine.

Progress for This Quarter

Initial results from an engine closure analysis were obtained for definition of brush seal loading during transient conditions.

Design analyses for the brush seal stability test were completed, and hardware was fabricated. The brush seal stability tests were completed. Two seals with different stiffness characteristics were tested at various pressure conditions associated with 7H operating conditions. Stability-pressure maps were generated for each test seal. Results of the test indicated that both the forward and the aft seals will operate in stable regions of the stability map for the designed seal stiffness. The design has also been shown to be robust relative to the cant angle of the bristles.

Seals and rotor from the first endurance test were carefully examined to identify any evidence of material changes in grain structure or micro hardness as a result of wear during the test. No indication of serious problems was observed.

Preparation for the follow up endurance test continued. This test will examine effects of shot peening of the 2-3 spacer on surface wear. Final design conditions for brush stiffness and

interference level will be examined. The final brush seal design will be completed and a detailed design review will be held.

Plans for Next Quarter

A follow up stability test and endurance test are planned. Seal design parameters will be finalized.

Technology Application

The results of this task will be used to specify requirements and characteristics for brush seals to be installed in the third stage diaphragm of the 7H turbine so that it can be tested during a no-load pre-shipment test of the full scale machine.

Section 2.2.4.14.4 (GTMTSR) Bore Tube Honeycomb Seal Rub Test

Objective

Redesign of the steam gland/bore tube sealing system has led to the use of honeycomb in combination with seal teeth. The high pressures associated with this seal require use of honeycomb sheet significantly thicker than existing experience. The objective of these tests is to assess wear/cutting characteristics of different honeycomb options and make a choice for use.

Progress for This Quarter

Honeycomb made from both HastAlloyX and Inconel 625 were tested with cell sizes of 1/16 inch and 1/8 inch. Two honeycomb-foil thicknesses were considered: 3 mil and 5 mil. The orientation of the honeycomb as defined by the bonded surfaces producing double wall thicknesses was also tested in configurations both parallel and perpendicular to the rotational direction. Tests were carried out in a rotating rig in the presence of steam and temperature consistent with the expected seal environment. Bearing load between tooth and honeycomb as well as friction loads and honeycomb temperature were measured, and the seals were examined after testing.

Based on these tests, the honeycomb seal material, cell size, and thickness were selected. The configuration selected had the lowest dynamic friction, (and therefore the lowest temperature rise) as well as the cleanest seal tooth cut.

Plans for Next Quarter

This task is complete.

Technology Application

Results of these tests will provide new technical experience for the choice of honeycomb in high pressure seal environments.

Section 2.2.4.15 (GTMTAR) Airfoil Repair**Objective**

Existing techniques will be evaluated and adapted for the material/geometry combinations unique to the ATS turbine airfoils to extend component life.

Progress for This Quarter

Development of the brazing and welding processes for first and second stage airfoil materials was continued. Prime joining processes have been downselected in most cases. The geometric design of the mock-up to demonstrate interactions of several high risk joints on the stage 1 nozzle is being confirmed, incorporating minor nozzle sub-component design changes. The stage 2 nozzle mockup is complete and specimens are being prepared. Filler materials for the stage 1 and stage bucket tip caps have been selected based on screening of various filler metals.

Plans for Next Quarter

Studies to enhance selected joining methods for hot gas path materials will continue, with focus on optimization of parameters to assure process robustness. Mock-ups for the high-risk joints on the first and second stage nozzle and evaluate results will be completed. Defect correlation will be continued.

Technology Application

This task will enhance processes and mechanical property data to optimize turbine airfoil hardware manufacture and subsequent operation.

SECTION 2.2.5 (GTTT) THERMAL BARRIER COATING TECHNOLOGY**Section 2.2.5.1 (GTTTSD) Coating System Development****Objective**

Plasma spray TBC coating processes will be developed for specific ATS combustion and turbine components. Both axisymmetric and non-axisymmetric plasma gun and part motions will be developed. Coating evaluations will consist of metallography, property measurements, and thermal cycling exposure. Computer simulations, motion trials on part replicas and spray trials on parts will be used for improving robot path planning accuracy. Improved process monitoring will be developed to increase process repeatability and control.

The TBC Manufacturing Technologies portion of the task will focus on integration and compatibility between TBC processing and other component manufacturing steps. Techniques to prepare components for spraying will be defined. Fixturing and masking, surface finishing techniques, drilling or masking of cooling holes, and methods to protect instrumentation will be developed as required.

The TBC Process and Diagnostics portion of the task will focus on achieving a better fundamental understanding of the TBC application process. Specific process conditions critical to the thickness and properties of the TBC system will be evaluated. Continuing work will focus identifying Critical-to-Process Characteristics (CTPs) for the ceramic top coat and metallic bond coat. The CTPs will be those directly controllable aspects of the coating process which most strongly influence process variability and TBC quality.

The TBC Non-destructive Evaluation (NDE) portion of the task will develop NDE techniques to measure attributes and properties of TBCs on turbine hardware that are relevant to manufacturing. The primary focus will be on development of methods to measure coating thickness. A secondary focus will be on development of methods to evaluate coating microstructure.

Progress for This Quarter

Robotic Motion Control and Programming Methods for ATS Airfoils

Eleven GE spray cells are capable of coating ATS airfoils using FANUC Robotics M710i/RJ2 systems. There are plans for an additional fifteen installations by 2001, which will bring the total number of GE spray cells capable of coating ATS airfoils to 26, located worldwide. As part of this initiative, standards for thermal spray and advanced robotics systems have been established, including installation, calibration, and programming. A robotics users group will be established within GE, to also include representatives from FANUC Robotics and Dynalog, Inc. This will assure that process transfer among the different cells can be readily accomplished, as well as facilitate sharing of TBC manufacturing best practices throughout GE.

The spray cell configuration includes a six-axis robot and two-axis turntable, which was optimized for coating turbine buckets, nozzles and shrouds; but is sub-optimal for coating combustor liners and transition pieces due to physical space limitations. Coating these parts requires only the six-axis robot, and can be accomplished in the current spray cells when the turntable is removed. A unique interface was developed jointly by GE and FANUC Robotics, which will enable the robotic system to operate in this configuration.

Robot alignment and calibration time was reduced by a factor of four using the new DynaCal™ System. A filter to correct the robot paths for the effects of variation in true part position due part-to-part dimensional variation and fixture alignment variation was developed and demonstrated. An off-line simulation tool to predict variation in TBC thickness and microstructure on ATS airfoils is being developed.

Coating Processes for ATS Components

Coating processes were developed and qualified for the following ATS components:

- Stage One Nozzle
- Stage Two Nozzle

- Stage One Bucket
- Stage Two Bucket
- Stage One Shroud
- Stage Two Shroud
- Combustor Liner
- Transition Piece

Associated manufacturing processes and NDE methods were also developed, as described in subsequent sections.

Bond Coat Processes

Note: This development is being conducted under an internal (non-ATS) program.

Candidate dense, protective thermally sprayed bond coats for ATS gas turbine airfoils and shrouds were identified. Specifications were written for single layer bond coats applied by Vacuum Plasma Spray (VPS) and High Velocity Oxy-Fuel (HVOF) processes. A new HVOF spray gun was implemented in manufacturing, requiring modifications to the spray process. Design of experiments and other Six Sigma tools are being utilized to generate transfer functions between critical spray parameters and coating performance. Two-layer bond coats and alternate bond coat chemistries are being evaluated using furnace cycling and oxidation burner rig exposure testing.

Coatings for CMAS Mitigation

Note: This development is being conducted under an internal (non-ATS) program.

TBC protective coatings were developed to extend turbine service conditions beyond those currently allowable by improving resistance to deposits of Calcium-Magnesium-Aluminum-Silicate (CMAS). An optimized multi-layer coating system deposited by Chemical Vapor Deposition (CVD) was developed. A pilot CVD coating reactor was installed at GE-CRD to coat ATS nozzles for cascade testing. Long-term durability testing was performed using the JETS thermal gradient test rig. An improvement in TBC life of greater than 50X compared to unprotected TBC was demonstrated at conditions more severe than the ATS gas turbine requirements.

TBC Manufacturing Technologies:

Procedures for each component were established; which include Manufacturing Process Plans (MPPs), Operations Methods, Quality Data Collection (QDC), Non-Destructive Testing (NDT) operations, and Final Audit. Local TBC repair procedures were developed and qualified for production parts.

A) Surface finishing methods

The first production ATS parts are being surface finished using manual abrasive polishing methods. These methods are not capable of maintaining final coating thickness within the limits required on ATS hardware, however. Conventional finishing techniques, such as tumbling and grit blasting, were also not acceptable because coating thickness uniformity cannot be maintained due to varying coating removal rates at locations such as fillets and leading edges of airfoils.

CNC grinding methods are being developed by GE and Huffman Corp. (Clover, SC) to ensure both acceptable surface finish and uniform material removal over all regions of the airfoils, fillets, sidewalls (nozzles), and platforms (buckets). The apparatus consists of a modified Huffman 6-Axis grinder with integrated CMM, GE diamond grinding wheels, and a GE eddy current system for on-line TBC thickness measurements. The as-sprayed coating thickness distribution is determined using eddy current measurements in combination with CMM touch probe measurements, which is required for acceptable control of the final coating thickness. Software for integrating these data was developed by GE-CRD and provided to Huffman.

Gage Repeatability and Reproducibility studies were performed for both the Huffman Touch Probe (TP) system and GE Eddy Current (EC) measurement systems. A computer simulation study was performed to define the work envelope, fixturing, and tooling requirements for ATS buckets and nozzles. Grinding trials on ATS buckets have been completed and the final TBC thickness met ATS requirements. Grinding trials on ATS nozzles will be performed in 1Q00.

B) Stage 2 nozzle doublet joint

Coating processes were developed and qualified for applying bond coat and top coat to the welded joint of the Stage 2 nozzle doublets.

C) Cooling Holes

A variety of techniques were evaluated for masking cooling holes as well as removal of excess coating from unmasked cooling holes. One of the latter techniques was downselected for production and transitioned to a vendor. However, it was found that oversizing the cooling holes in combination with modification of the robot program was most successful in producing coated cooling holes of the correct final size and shape.

TBC Process and Diagnostics:

The TAFAPlazjet gun was selected for the next generation TBC process. This gun has the capability of achieving similar or better TBC properties than the Metco 7MB gun at longer standoff distances and up to 5X higher powder injection rates. Plazjet guns were installed in three GE spray cells, and will be used for both production and process development. A new spray process was developed at GECD and successfully transitioned to manufacturing, resulting in improved TBC thickness and surface finish as well as reductions in process cycle time of nearly 3X for F-class

production hardware. Process development was greatly accelerated through leveraging of diagnostic tools developed in a recently concluded ATP program.

A comprehensive TBC process/properties database is being accumulated, including tensile, modulus, deposition rate, thermal conductivity, surface roughness, and furnace cycle life. Regression models to predict TBC properties, including both mean and standard deviation, from the controlling process parameters are being developed as part of the GE "Design for Six Sigma" (DFSS) initiative. A TBC thermal conductivity model will be developed through a two year collaborative effort with NIST beginning in 1Q00.

GE-CRD is an industrial member of the Thermal Spray Consortium at the University of Toronto, which is developing transfer functions to predict TBC microstructure evolution using advanced experimental, numerical and statistical methodologies. Simulation software developed by the consortium will be beta tested by GE-CRD in 2000.

Non-destructive TBC Thickness Measurement:

An automated ceramic coating thickness measurement system consisting of a flexible eddy current probe in combination with a multi-axis contact probe scanner was developed. Installed Coordinate Measuring Machines (CMMs) are used as the scanning devices. Several hundred inspection points can be measured in under fifteen minutes, which reduces inspection time by over 5X compared to manual measurements. Gage R&R studies were completed, which demonstrated that the measurement precision and reproducibility are well within the requirements for ATS parts.

An improved flexible eddy current probe was developed, both to reduce the probe cost and to improve the probe durability. A probe contact simulator, consisting of a single axis actuator with a servo controller was developed in order to test probe life. An improvement in probe life by a factor of 20X was demonstrated.

The development CMM system was upgraded to allow both on-line and off-line programming via a new PC-DMIS system. This system allows for development and simulation of the measurement process directly from CAD files (UG, IGES, etc.) without using actual parts or fixtures. PC-DMIS also supports reverse engineering of complex shapes, such as buckets and nozzles.

Non-destructive TBC Microstructure Evaluation:

A Laser Ultrasound Test (LUT) was developed for Non-Destructive Evaluation (NDE) of TBC adhesion. A Nd:YAG laser is used to produce a shaped source beam on the target coated part, generating an ultrasonic Lamb wave that propagates almost completely within the ceramic coating. A laser interferometer senses the propagating wave signal, which is stored on computer and analyzed for frequency dispersion content; i.e., ultrasonic velocity as a function of frequency.

Young's modulus and tensile properties are extracted from the measured signal; these data have been validated by destructive measurements on coupons. The ATS Cascade Nozzles as well as production buckets and thermal-mechanical fatigue (TMF) test specimens were extensively

evaluated to further validate and refine these correlations. Good correlations were observed between LUT tensile predictions and destructive pull-tests for coupons. However, some of the microstructural variation present on the components resulted in loss of signal due to attenuation, as well as a different transfer function from that obtained on the coupons. As a result of these inconsistencies, software for coating “fingerprint” evaluation was developed. This software compares the LUT signature for an unknown coating with a database of signatures from coatings of different microstructures. The signature that most closely matches the unknown coating is selected from the database, resulting in predictive accuracy for coating tensile strength of 10-20%.

Quality Function Deployments (QFDs) were performed with engineering, manufacturing and services to define the functional requirements for the LUT system. Cost reduction of the instrumentation was very important. A low cost Sagnac interferometer developed jointly by Northwestern University and GE-CRD meets all initial requirements. The prototype instrument was delivered to GE-CRD in 1999. A competing technology, using a photorefractive interferometer, meets performance targets at greater standoff distance, but at higher cost. Based on the output of the QFDs, the Sagnac interferometer will be developed as a first generation system for both manufacturing and field inspection applications, while the photorefractive technology may be developed as a second generation system for manufacturing, where long standoff is desired.

Discussions were held with two universities {University of Connecticut, University of California – Santa Barbara} developing laser fluorescence as a technique for coating evaluation. These universities are funded under the Advanced Gas Turbine Systems Research (AGTSR) program. Collaborative research and development between GE-CRD and these universities will be performed under appropriate terms and conditions, outside the scope of the AGTSR contracts.

Plans for Next Quarter

Note: All activities other than part coating and CNC grinding development will be conducted under non-ATS programs.

Robotic Motion Control

Evaluate the new FANUC Robotics RJ3 controller.

Improve thickness predictions on the ATS bucket replica using measured gun/part velocity and orientation data in place of “taught” path data. Evaluate effects of particle “glancing” and “rebounding” on the spray footprint for different simulated geometries, gun aging conditions and powder types.

Part Coating

Coat ATS production Stage 1 nozzles and welded joints of ATS Stage 2 nozzles.

TBC Manufacturing Technologies:

Demonstrate CNC grinding capability for ATS nozzles.

TBC Process and Diagnostics:

Begin a two year collaborative effort with NIST for development of an object-oriented TBC thermal conductivity model.

Non-destructive TBC Thickness Measurement:

Initiate life testing of new eddy current probe designs.

Non-destructive TBC Evaluation:

Fully evaluate the Sagnac interferometer. Determine accuracy and accept/reject criteria for LUT inspections.

Install a new high-speed IR system for development use.

Technology Application

The process for applying air plasma spray TBC to ATS combustion and turbine components will be defined. This process will define the baseline upon which coating durability will be evaluated and evolutionary improvements will be made.

Section 2.2.5.1.1 (GTTTSD) Effects of TBC Surface Finish on Drag**Objective**

TBC coatings are used on the nozzles and buckets in the H turbine. Current TBC surface finish specifications call for polishing the TBC coatings from an as-applied finish (approximately 400 micro-inches) down to 60 micro-inches in order to reduce aerodynamic drag. The current specification of 60 micro-inches is based on design practices with metallic surfaces. Polished TBC surface finishes are physically different from machined metallic finishes, however, and there are no data that relate TBC surface finishes to the aerodynamic drag they produce. Polishing TBC-coated surfaces down to 60 micro-inches is both challenging and costly and may not be necessary. This task will experimentally determine the effect that TBC surface finish has on drag so that an informed, appropriate surface finish specification can be established.

Progress for This Quarter

Note: Testing is being funded under an internal GE (non-ATS) program, and results are reported to maintain continuity in the overall H program.

Wind tunnel airfoil drag testing of the smooth airfoil was completed. The airfoil TBC spray fixture was designed and built. The airfoil TBC spray coating path programming was completed.

Plans for Next Quarter

Drag measurement testing will continue, and the results will be used to determine the TBC surface finish specification for the H machine TBC coated hot section hardware.

Technology Application

The results of this test will provide data for determining a surface finish design specification for TBC-coated turbine nozzles and buckets. The data can be also be used to calculate tradeoffs of finishing costs and turbine efficiency.

Section 2.2.5.3 (GTTTDD) TBC Design Data and Life Analyses

Objective

Failure modes in advanced TBCs will be identified, classified, and defined using empirical methods. Experiments will be performed to find key relationships among plasma spray processing variables, coating microstructure, coating physical and mechanical properties, and coating performance under simulated ATS conditions.

The relative contribution of oxidation and cyclic damage to the failure of different substrate / bond coat / top coat systems will be evaluated in order to estimate the TBC life in the ATS gas turbine. This will be accomplished by furnace cycle testing TBC systems using a series of dwell times per cycle (0.1 to 20 h/cycle) and dwell temperatures (1037-1148°C, 1900-2100°F), and incorporating the results into an existing cumulative damage model. Accelerated testing at temperatures below 1037°C (1900°F) will be accomplished using a tensile Thermal-Mechanical Fatigue test, which superimposes cyclic mechanical strain upon the cyclic thermal strain. In support of the modeling approach, microstructural features of the ceramic top coat and metallic bond coat will be examined.

Numerical analyses will be performed to determine TBC stress states expected in ATS turbine components and in laboratory thermal cycling tests. The influence of the TBC stresses on TBC failure modes will be examined. Specially developed finite elements will be used for modeling the behavior of the interface cracks and free-edge stress singularities. The effects of bond coat roughness on TBC stress state, crack driving forces, and delamination failure will be examined. Parametric studies to determine the effects of bond coat and top coat properties on the TBC stress states will be performed.

The spatial and run-to-run variability of TBC thermal conductivity will be evaluated. Improved understanding of this variability is essential, because the variation in TBC thermal conductivity can be several times greater than that seen in metals due to variations in TBC microstructure, leading to design inaccuracy. Different methods of measuring thermal diffusivity and conductivity on flat and curved samples will be evaluated. The gas pressure dependence of thermal conductivity as a function of temperature will be measured. The results will be used to estimate the thermal conductivity of TBC at ATS conditions. The effect of thermal aging on TBC thermal conductivity will be quantified.

Progress for This Quarter

The relative contributions of time-dependent (oxidation) damage and cycle-dependent (fatigue) damage to ultimate failure of the TBC are being evaluated through mechanical tests as well as metallurgical and NDE evaluations. Mechanical tests include thermal-mechanical fatigue, compression shear, tensile, ballistic impact, and hardness tests. Thermal-Mechanical Fatigue (TMF) data will be used with Furnace Cycle Test (FCT) data to predict or estimate TBC life. Other data will be used to rank TBC based on empirical parameters.

Test specimens comprising four different substrate / bond coat / top coat systems representing different ATS components were prepared. One of the TBC systems is a duplication of the TBC applied to the ATS Cascade Nozzles. This TBC was deposited using certain process conditions which deviated from standard practice, and may have contributed to the early TBC spallation observed on some nozzles.

Specimens were machined from Rene N5, GTD111, GTD222 alloys. Two types of specimen were prepared: 1.00 diameter x 0.125 inch thick buttons and 7 inch long x 0.250 inch thick TMF bars. After completion of TBC deposition, the test samples were heat treated in vacuum as per the requirements for the respective substrate alloys. Some samples are being thermally aged in air in order to study the influence of exposure on the TBC properties and impact behavior. All GTD111 and GTD222 specimens were overaluminided using a NiAl coating to protect the substrate metal from oxidation during high temperature testing.

Furnace Cycle Testing

Conventional (“porous”) and advanced (“dense vertically cracked” or “DVC”) TBC specimens were furnace cycled at 1148°C (2100°F) and 1093°C (2000°F) using dwell times of 0.1, 0.75, 10, and 20 hours per cycle. Furnace cycle testing at 1037°C (1900°F) was begun, using dwell times of 0.1, 0.75, and 10 hours per cycle. The 0.75 hour tests were completed. To date, 25665 and 1092 cycles have accumulated for the 0.1 and 10 hour tests, respectively.

The majority of specimens were cycled to failure, although some specimens were removed at intermediate times for tensile adhesion testing and laser ultrasound measurements. A small number of specimens were intentionally exposed to two different dwell times in order to test the influence of thermal history on remaining TBC life. Additional FCT tests were begun on several new substrate / bond coat / top coat systems, as described above.

The data was fit using the cumulative damage model for the cases of parabolic and cyclic oxidation. In both cases a reasonable fit was obtained to the FCT data; however, the two curve fits yield markedly different estimates for the TBC spallation lives at low temperatures. Examination of the oxide growth kinetics at 1093°C (2000°F) indicated that a two-stage parabolic oxidation damage model is appropriate for one TBC system.

Thermal-Mechanical Fatigue Testing

The Thermal-Mechanical Fatigue (TMF) testing is being performed by Materials Characterization Laboratory (Scotia, NY). Development activities included construction of a collapsible hot surface ignitor furnace for sample heating/cooling, writing TMF test software modules, setting up a data acquisition system, and setting up a digital camera for recording TBC surface condition during testing. A new GE Specification was prepared for TMF testing TBC coated superalloys.

Trial TMF tests revealed that the initial test specimen geometry was susceptible to buckling under compressive loading. A new gripping method was developed, which eliminated buckling for compression strain ranges up to -0.5%. Modifications to the furnace and grips were also made following the first tests to improve durability. The test rig can be used for both in-phase (maximum stress/strain coincides with maximum temperature) and out-of-phase (maximum stress/strain coincides with minimum temperature) tests.

Two in-phase TMF tests were performed on single crystal N5 coated with APS NiCrAlY bond coat and APS DVC top coat, at maximum conditions of 982°C (1800°F) and -0.3% or -0.5% strain. The tests were terminated after 946 and 315 cycles, respectively, without TBC failure. The condition of the TBC applied to the TMF specimens was evaluated using non-destructive laser ultrasound and infrared thermal imaging techniques. Measurable TBC degradation did occur during TMF testing, even though the TBC remained visibly intact.

Two in-phase TMF test were performed at maximum conditions of 1066°C (1950°F) and -0.5% strain. TBC failure occurred by top coat delamination without specimen buckling. Non-destructive and metallographic examinations were performed. Metallographic examination showed that the bond coat exhibited minor oxidation, but significant additional damage occurred in both the top coat and bond coat due to the superimposed mechanical strain. This effect resulted in a significant reduction in TBC life compared with FCT data at the same temperature and dwell time, which is consistent with the life model. The life model will be further refined when additional TMF data is available.

Thermal Conductivity

The highest priority tasks in 1999 were: 1) determine the gas pressure dependence of thermal conductivity, 2) determine thermal conductivity of TBC following field service, and 3) better quantify the spatial variability of thermal conductivity on ATS buckets and nozzles. In addition, several equipment issues were identified and corrected.

A) Planar samples

Measurement of TBC thermal conductivity was completed on samples aged at 1204 and 1315°C (2200 and 2400°F) for 10 and 100 hours. These data were combined with data from measurements performed in 1997 on samples aged at 1038, 1204 and 1315°C (1900, 2200 and 2400°F) for 1000 hours to create new design curves. 95% confidence limits on these data were

calculated, providing a measure of data quality and allowing the data uncertainty to be included in thermal calculations.

A furnace capable of testing thermal diffusivity of TBC samples at pressures up to 30 atmospheres was installed at GECRD. The gas pressure effect over 1-25 atmospheres was evaluated for the aged samples. These data validate the predictions published in 1997 (Mogro-Campero et al., Surface and Coatings Technology 94-95, 102-105, 1997).

Thermal conductivity was measured as a function of TBC thickness. A positive, but minor correlation was observed with increasing thickness, which is consistent with the presence of a previously suspected radiation component.

B) Curved samples from parts

Evaluations of as-deposited and aged free-standing TBC from ATS Cascade nozzles and field returned buckets and shrouds were performed. Samples of as-deposited TBC are being prepared from an ATS bucket. Systematic variation in thermal conductivity was observed on the nozzles according to location. The source of this variation was the TBC microstructure, which is strongly dependent upon the spray gun motions and local part temperature. An improved waterjet sectioning technique was developed for obtaining specimens from nozzle fillets.

Plans for Next Quarter

Note: All activities will be conducted under non-ATS programs.

Thermally age TBC test samples in air at various temperatures and times prior to compressive strain and impact testing.

Furnace Cycle Test

Continue testing at 1038°C (1900°F).

Thermal-Mechanical Fatigue Testing

Perform additional TMF tests to refine and calibrate the TBC life model for the effect of superimposed mechanical strain.

Evaluate a new specimen which will permit testing at strain ranges above -0.5%. Assess suitability of alternate heating arrangements (such as induction and resistance heating) and gripping methods to minimize potential sample buckling in TMF tests with strain ranges greater than -0.5%.

Thermal Conductivity

Complete thermal conductivity measurements on samples from ATS buckets and field-aged parts.

Technology Application

The results of this task are used to update the design databases. In addition, a database will be established which will link TBC properties and durability in laboratory tests to TBC durability in the ATS gas turbine. This database will be used ultimately be used to predict TBC life as a function of temperature and strain at specific locations on ATS gas turbine components. The database will also be used to identify process improvements to the baseline TBC which result in improved properties and durability.

SECTION 2.3 (CC) COMBINED CYCLE INTEGRATION

SECTION 2.3.1 (CCUA) UNIT ACCESSORIES

Objective

Development of the four new unit accessories is critical to the development of the ATS Gas Turbine in order that the gas turbine meet its performance goals and function properly. The cooling air cooling system is required to maintain temperature within sections of the gas turbine within acceptable limits. The steam cooling system is required to cool the turbine hot gas path parts while meeting performance goals for the gas turbine. The clearance control system is designed to enable the gas turbine to operate at a higher efficiency than would otherwise be possible without the system. The exhaust diffuser shall be designed such that a pressure recovery will be realized thus increasing the performance of the ATS gas turbine.

Progress for This Quarter

Cooled Cooling Air System

The full scale test of the 9H cooled cooling air skid was considered and rejected, based on high testing costs. Efforts were then put into the stress analysis used to validate the current design and hardware. The results of this have been ongoing and final conclusions can be drawn from the data in the near future. This analysis will have important benefits for the 7H design, and impacts on the 7H plant arrangement since the analysis may impact skid footprint and piping connections.

Steam Cooling System

Because the steam cooling valves are placed mainly in piping designed and engineered by the Architectural Engineer, an important coordination meeting was held to ensure mutually correct design data and, most critically, valve-piping interfaces. Changes have been made based on this, including some that will result in a significant reduction in field installation work necessary. These improvements will be carried over for the 7H design to ensure coordination between GE and the Architectural Engineer on the first 7H.

Fabrication of the valves is continuing, with the above changes incorporated.

Clearance Control System

The new filtration requirements considered during FSNL testing have been implemented. These are considered to be more robust than the previous design requirements, and should ensure any problems with debris in the Gas Turbine inner shell does not result in a failure of the filtration system. This change will also be carried over to the 7H design.

The analysis of the possibility of an alternate, simpler air supply has been continuing. It now appears likely that it can be implemented in time for use in the 7H, FSFL pre-shipment test.

Exhaust Diffuser

Due to some simplification of the piping integrated with the diffuser, the 9H diffuser will require slight reworking to accommodate these changes. The changes will result in a more cost effective, reliable design for the H diffuser. This change will be carried over to the 7H. Another addition has been the completion of temporary support steel to assist in the initial erection of H diffusers, because of their higher complexity over mature designs. A further improvement for the 7H is changes in flange location in the piping penetrating the diffuser to allow for easier, quicker installation.

Plans for Next Quarter

Cooled Cooling Air System

The design of the 7H skid was delayed, waiting for the results of the 9H skid stress analysis. The results may affect the skid's design, and changes from the 9H will be coordinated with the Architectural Engineer for the overall plant design for the 7H plant.

The 9H skid is now awaiting shipment, and preparations for that will also require attention on our part.

Steam Cooling System

The production of the 7H data blocks and the continued fabrication of the 9H valves will continue in the next quarter. The first effort will need coordination with the rest of the GE organization to ensure the timely production and agreement to all the contents. The second will require communication with the valve supplier to maintain delivery dates.

Clearance Control System

Finalization of the alternate air source for use in the 7H hardware will be the main focus of coming efforts. Once this occurs, the 7H design work can proceed, with coordination of the skid into the power plant with the new air source, which will require work with the customer's Architectural Engineer for proper plant design.

Exhaust System

The 3Q00 will be spent in completing the small improvements required to the current 9H diffuser. These changes will be incorporated into the 7H design as well. Because of delays due to the changes in the hardware, the test fabrication has been rescheduled for late 3Q00. There may be further changes to the 9H hardware, and certainly lessons learned to be applied to the developing 7H design.

Technical Application

Development of the cooling air cooling system, the steam cooling system, the clearance control system and the exhaust diffuser are all critical to successful operation of the ATS gas turbine. Each system is also critical to the high efficiency rating that the ATS gas turbine will achieve. Therefore development of these system will continue in order that the ATS gas turbine will meet these design goals.

SECTION 2.3.2 (CCCL) CONTROLS

Objective

An integrated plant control system will be developed and designed that will be suitable for the advanced gas turbine combined cycle power plant. Specifications of control equipment requirements will be prepared. Control and protection strategies will be developed for gas turbine steam cooling and integration with the steam turbine and heat recovery steam generator (HRSG). Control system dynamic behaviors will be studied by dynamic simulations. Specifications of control algorithms will be prepared for implementation in the control system program.

Progress for This Quarter

The study of control loop dynamics continued, with the focus on combined cycle operability and application to the launch site. Initiated simulation study of contingency operations such as responses to load rejection and plant trip scenarios. Continued control program coding in preparation for the launch site. Continued development of control and protection algorithms for the steam cooling system and coordination with the steam cycle operation. Control panels configured in a combined cycle test environment are in place. Field testing of the triple redundant control system continues at a test site, collecting data to verify operational reliability.

Plans for Next Quarter

The study of control loop dynamics will continue, using actual control hardware. Control program coding for the gas turbine and steam turbine will continue, and will be installed into control panels, with specific application to the launch site. Assembly of control equipment for the launch site will be initiated, and verification of the control programs will be performed using this set of equipment. Field testing of the triple-redundant control system will continue with emphasis on operational reliability

Technology Application

The integrated plant control system conceptual design for the STAG 109H configuration will be very similar to that of the STAG 107H ATS plant.

SECTION 2.3.3 (CCRA) RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) ANALYSIS

Objective

An evaluation of the reliability, availability, and maintainability (RAM) of the 7H equipment will be performed. The basis for the work will be the Electric Power Research Institute (EPRI) High Reliability Controls and Accessories Study. The RAM analysis will include: the flange-to-flange gas turbine, heat recovery steam generator, steam turbine, controls and accessories, electrical generator, and balance of plant equipment. A failure modes effects analysis (FMEA) will be included.

Progress for This Quarter

Reliability assessment of the fuel moisturization system is completed. The results have been provided as input to the design teams to incorporate into the full analysis of the system.

Reliability assessments of both the Fuel Gas Heating System and the Fuel Gas Compressor have been completed. The evaluation of the Fuel Gas Compressor included a review of three (3) arrangements; 1x100% compressor, 2x100% compressors, and 3x50% compressors.

The reliability analysis of the spoolie has been updated, by looking at the impact on operation by failure of one or more spoolies. Additionally, the overall rotor steam delivery system reliability assessment has been updated with current design lives of the key components.

Reliability assessments of critical accessories systems have been updated with the current design, including; Lube Oil, Seal Oil, Lift Oil, Hydraulic Control and Trip, and Clearance Control.

Plans for Next Quarter

Continue to update all accessories system reliability block diagram analyses with current design.

Finalize the overall Steam Cooling System reliability assessment including delivery to the rotor and stator components.

Continue to update flange-to-flange reliability assessment with updated design lives from design engineering. This includes looking at estimated B1 lives at the failure mode level.

Continue stress analysis of the stage 1, 2, and 3 wheel/bucket dovetails.

Technology Application

The FMEA results will be applied to the design of the 9H and 7H hardware, with special emphasis on the components involved with the steam-cooling aspects of the design. The reliability assessments will affect the design of various systems across the H combined-cycle plant.

SECTION 2.3.4 (CCSD) COMBINED CYCLE SYSTEMS DESIGN

Objective

Combined cycle system optimization analyses will be performed for cost/performance characteristics of the total plant. Steady-state modeling will be used to calculate the detailed plant performance. Dynamic modeling of load change sequences (e.g., startup and load rejection) will be used to specify control system design and assess operability.

Progress for This Quarter

Optimization studies for the combined cycle sub-systems continued. Planning continued for the characterization testing of the launch S109H plant using a Six Sigma quality approach to define test objectives (CTQs) and constraints.

Preparation for detail design of the launch S107H plant continues, with a focus on areas where the 60Hz design differs from the 50Hz design, and updates to steady state models based on 7H FSNL test data. Major balance of plant equipment functional specifications were developed and issued for bid.

Transient operability simulations continue using the transient dynamic model (TDM) to validate control strategies and algorithms for the launch S109H plant. Steady state and transient system operability is being evaluated in detail to support final control settings. State point data from these simulations is also being used to validate component design life against normal and contingency transient operating conditions.

Plans for Next Quarter

Optimization studies for the combined cycle sub-systems will continue. Refinements to both the S109H and S107H designs will continue based on incorporation of gas turbine FSNL test data. Detail design of the launch S107H plant will begin, including updates to the S107H TDM to the launch site specific configuration and hardware data.

Transient operability simulations will continue using the TDM to validate and finalize control strategies and algorithms. Model updates will be made to allow support of characterization test plan development.

Technology Application

Operability evaluation of the STAG 109H configuration will be directly applicable to the STAG 107H ATS plant. Cooling-air cooling and fuel heating system conceptual designs will be very similar for the STAG 107H ATS plant.

SECTION 2.4 (MF) MANUFACTURING EQUIPMENT AND TOOLING

Objective

The materials, equipment, tooling, and processes required to produce the 7H and 9H turbines will be identified, designed and procured. Manufacturing schedules will be established to support ATS pre-commercial demonstration goals. Manufacturing schedules and cost will be defined. Manufacturing will be conducted to these plans.

Progress for This Quarter

The 9H Gas Turbine was returned to the test stand in preparation for re-assembly for shipment. The rotor was installed in a special building in preparation for installation of the modified bore tube. The first lot of stage 2 nozzles was assembled into the inner shell.

Also in this quarter the 7H Gas Turbine was disassembled after the FSNL test. The casing structure was moved to a temporary storage building, and the rotor and stator components were shipped to various suppliers, and to the Houston Service Shop for evaluation and rework.

Plans for Next Quarter

During the next reporting period, the 9H rotor will have the full steam system installed and tested, the inner shell assembly will be completed, and the unit will be reassembled in preparation for shipment.

The 7H Gas Turbine rotor and components will start rework at suppliers. The compressor rotor rework will be completed and put into storage, and the turbine rotor will be disassembled. The wheels and spacers will be sent to suppliers for finish and mod-machining. Casting trials for the FSFL pre-shipment airfoils will commence.

Technology Application

Development of the turbine wheel forging dies and the ultrasonic inspection techniques are the first application in forgings of this size and will be used to provide high-strength, high-temperature material that is compatible with the steam cooling environment in the ATS turbine rotor. The mockups are being used to ensure fit-up of all components in very restrictive areas of the turbine. An electronic simulation of these areas is being done in parallel to develop simulation technology for future applications. The TBC robot controllers will provide the thickness control for the TBC coating that is required for proper heat transfer properties in the steam-cooled turbine airfoil components.

SECTION 2.5 (IG) INTEGRATED GASIFICATION AND BIOMASS FUEL

Objective

An assessment of the ATS will be performed as part of an efficient and environmentally compatible integrated gasification combined cycle (IGCC) power generation system. Modifications to the gas turbine to accommodate the high mass flow resulting from the low heating value fuel gas and nitrogen injection for low NO_x emissions will be identified. Analyses will be run to optimize the integration of the steam cycle with one oxygen-blown entrained flow gasifier and gas cleanup system and integration of the gas turbine with the air separation unit. IGCC system performance will be analyzed for one coal composition at ISO ambient air conditions.

Progress for This Quarter

Work was initiated on predicting H machine performance as part of an integrated gasification combined cycle (IGC) power generation system. Performance was based on the 9H (current design) integrated with one entrained flow O₂ blown gasifier, an air separation unit, and cold gas clean-up for one coal at ISO ambient conditions.

Plans for Next Quarter

The ATS IGCC task will be completed and a Topical Report will be written.

Technology Application

Integrated gasification combined cycle (IGCC) and biomass fuel based applications are potential uses for the ATS machine as part of an economical and environmentally compatible power generation system.

SECTION 2.7 (PM) PROGRAM MANAGEMENT

Objective

Within GE Power Systems (GEPS) Engineering, an ATS Program Office will be established and a Program Manager and a Contract Administrator will be assigned. The Program Manager will direct the overall activities of the Program Office, and will have responsibility for reporting to DOE and ensuring that the program goals are achieved. The Program Office is responsible for communicating contract requirements, authorizing applied labor and expenses for material and services, scheduling, monitoring, and reporting cost and technical performance. Additional responsibilities include coordinating ATS activities with GE Corporate Research and Development (CRD) and GE Aircraft Engines (GEAE). The assigned Contract Administrator will support the Program Manager in all administrative matters. All materials and equipment acquisitions will be closely monitored by the Program Office with support from the Finance and Sourcing organizations.

Actual scope, schedule, and budget will be tracked against plan. An integrated program plan will be maintained, including a detailed Work Breakdown Structure, which accurately describes the planned work, reflecting all changes in work scope or schedule. The integrated program plan includes the implementation and coordination of all program support procedures and initiatives such as Target Costing, Key Quality, and Design for Manufacturing.

Reports will be prepared to serve both DOE and GE needs for oversight and monitoring, including quarterly reports, annual reports, and topical reports. A final report will be prepared at the completion of the cooperative agreement. Reports specified in the Cooperative Agreement's Financial Assistance Reporting Requirements Checklist will be supplied. Technical papers will be submitted for presentation to professional society meetings. Open communications will be maintained with DOE and the Industry Advisory Board.

Progress for This Quarter

A Quarterly Program Review was held at the GE Power Systems Schenectady, NY facility, and at the GE Corporate Research and Development (GE-CRD) Niskayuna, NY facility. The Review covered the status of the ATS program to date, 1Q00 program highlights, remaining Budget Period 4 (2000) component testing milestones and schedules, and presentations on the following: H Nozzle Cascade Test Program, H Combustor Design/Test Program, 7H FSNL Test Program, Turbine Rotor Test Program, and a tour of the Engineering Lab.

The review at GE-CRD covered the following: CRD Overview, Laser Flash Wall Thickness Measurement, Exhaust Duct Assembly Computerized Visualization, TBC Coating Facility, Single Crystal Casting Facility, Metallurgy Building Tour, Combustion Test Facility Tour, and Flow Test and CFD Predictions.

Plans for Next Quarter

A Program Review will be held to review the remaining Budget Period 4 component testing milestones and schedule.

SECTION 2 TECHNICAL PROGRESS REPORTS: TASKS COMPLETED BEFORE THIS REPORTING PERIOD

SECTION 2.1 (NE) NEPA

Objective

A draft topical report was prepared that provided the environmental information associated with Phase 3, Technology Readiness Testing, as specified in the National Environmental Policy Act (NEPA). DOE used this information to prepare the NEPA documentation for Phase 3. DOE reviewed the report and advised the participant of its acceptability. A final report was then submitted.

A second draft topical report was prepared that provided the environmental information associated with Phase 4, Pre-Commercial Demonstration, as specified in NEPA. DOE used this information to prepare the NEPA documentation for Phase 4. DOE reviewed the report and advised the participant of its acceptability. A final report was then submitted.

At DOE's request, Phase 4 was deleted and Phase 3 was restructured (as Phase 3R) with the inclusion of the 7H FSNL test at the GE Greenville, SC, facility. This change necessitated the generation of an environmental assessment of the Greenville assembly and test facility.

Plans

This task was completed in 4Q97.

Technology Application

The NEPA report provides documentation that GE Power Systems is in compliance with all applicable environmental, health, and safety laws and regulations, and has the required permits and licenses necessary for compliance.

SECTION 2.2.1 (GTAD) AERODYNAMIC DESIGN

Objective

A four-stage turbine was designed to achieve ATS performance goals. Advanced aerodynamic technology (sometimes called 3D aerodynamics) pioneered at GEAE was applied to each stage to maximize performance and meet mechanical design requirements required by steam cooling technology.

The 7H (60 Hz) and 9H (50 Hz) turbines have similar flowpaths and a common rotor but require different aerodynamic designs. Performance requirements for the 7H and 9H turbine aerodynamics are the same.

Plans

This task was completed in 4Q96.

Technology Application

Advanced aerodynamic technology (sometimes called 3D aerodynamics) pioneered at GEAE was applied to each stage to maximize performance and meet mechanical design objectives required by steam cooling technology.

Section 2.2.2.3.1 (GTFFTR) Turbine Rotor Mechanical Analysis**Objective**

The objective of this task was to provide thermal and mechanical design and analysis support for rotor components of the ATS gas turbine. Analyses were run to determine temperature, displacement, and stress distributions for various components of the ATS gas turbine rotor. Initial designs and concepts were analyzed, compared, and modified to meet design specifications with respect to stress levels, LCF life, yielded volume, residual displacement, rabbet closure, etc.

Plans

This task was completed in 4Q97.

Technology Application

The analysis performed and the resulting design features were used to robustly design an ATS gas turbine rotor that meets cycle life requirements.

Section 2.2.2.3.2 (GTFFTR) Wheel Forging Stress Analysis**Objective**

The objective of this task was to determine the influence of residual stresses on overspeed design limits for IN706 and IN718 wheel forgings. Overspeed tests on a 7F first-stage wheel (IN706) indicated that there might be large residual stresses in the wheel forgings after heat treatment. These residual stresses might have an effect on fatigue life and would affect residual displacements. The effect on residual rabbet deflections is particularly important since rabbet opening/closure as well as rabbet loading and local plasticity may be affected. If residual stresses turned out to be significant in the ATS gas turbine (IN718) as well, they would have to be included in the design calculations. The residual stress calculation would be done on the 7F wheel first to correlate the analysis with available test data. The procedure would then be applied to the ATS wheels.

Plans

This task was completed in 4Q99.

Technology Application

The dovetails were highly stressed, and, in addition, there were severe thermal gradients in the dovetail region. Detailed 3D stress analyses were required to ensure that the dovetails and the wheels meet design guidelines for the ATS turbine rotor.

Section 2.2.2.3.2 (GTFFTR) Wheel Forging Residual Stress Analysis

Objective

The objective of this task was to determine the influence of residual stresses on overspeed design limits for IN706 and IN718 wheel forgings. Overspeed tests on a 7F first-stage wheel (IN706) indicated that there might be large residual stresses in the wheel forgings after heat treatment. These residual stresses might have an effect on fatigue life and would affect residual displacements. The effect on residual rabbit deflections is particularly important since rabbit opening/closure as well as rabbit loading and local plasticity may be affected. If residual stresses turned out to be significant in the ATS gas turbine (IN718) as well, they would have to be included in the design calculations. The residual stress calculation would be done on the 7F wheel first to correlate the analysis with available test data. The procedure would then be applied to the ATS wheels.

Plans

This subtask in support of the ATS gas turbine design was completed in 4Q97.

Technology Application

Residual stress levels will affect the deformation of the wheel during overspeed and can affect fatigue performance. If significant residual stresses remained after the aging process, the residual stresses would be included in the design calculations.

Section 2.2.2.3.3 (GTFFTR) Rotor Steam Circuit Analysis

Objective

The objective of this task is to assess rotational and 3D effects on the flow within the rotor steam circuit components whose performance is strongly dependent on these effects. The steam distribution into the buckets, for example, depends on the performance of the manifolds to ensure that the buckets are adequately cooled. Hydraulic losses can be better estimated when 3D effects are considered. The rotational and 3D effects will be assessed using computational fluid dynamics (CFD), and the results of the analyses will provide the basis for design modifications if necessary.

CFD techniques will be applied to determine 3D and rotational effects in critical components of the 9H and 7H rotor steam cooling circuit. Component performance (e.g., pressure drop and flow distribution) will be established, and means for improving component performance will be investigated as needed.

Plans

This task was completed in 4Q99.

Technology Application

The results of this task define the hydraulic performance of the overall steam distribution circuit and of the individual components it comprises. Performance predictions of various designs were used in tradeoff studies to select the baseline concept of the overall steam distribution strategy and the specific design of the scroll, and the supply and return manifolds. Drawings were issued that incorporate the design modifications arrived at through the performance of this task. As the design of the component evolves in response to mechanical constraints, this task ensures that hydraulic performance is not compromised. This task also identifies performance improvements to achieve critical-to-quality criteria (CTQs).

Section 2.2.2.3.4 (GTFFTR) Turbine Rotor Shaft Temperature Analysis - #2 Bearing

Objective

The objective of this task is to investigate design options that would result in a minimum temperature of the shaft surface in contact with oil and/or air oil mist, and a maximum thermal gradient in the area of the oil seals in the #2 bearing.

Allowable temperatures in the seal forward of the 9H turbine #2 bearing are limited due to the accelerated decomposition of lubricating oil at high temperatures. Thermal gradients are also limited in that uneven thermal expansion of the shaft will adversely affect seal clearances and performance.

Plans

This task was completed in 2Q98. Further analyses supporting preliminary and detail design of the AWS are being completed as part of the Turbine Rotor Design task and reported in Section 2.2.2.3.

Technology Application

All the design options evaluated in this study were considered for ATS turbine rotor design in a detailed follow-up study using a fluid element analysis approach to better simulate the heat transfer boundary conditions in the current modeling effort.

Section 2.2.2.4.1 (GTFFTB) S1B and S2B Wheel Dovetail Analysis

Objective

The objective of this task was to perform 3D thermomechanical analyses of ATS gas turbine rotor dovetails, bolt holes, and steam-cooling holes. The dovetails are highly stressed and, in addition, there are severe thermal gradients in the dovetail region. Detailed 3D stress analyses are required to ensure that the dovetails and the wheels meet design guidelines.

Plans

This task was completed in 2Q97.

Technology Application

The dovetails were highly stressed and, in addition, there were severe thermal gradients in the dovetail region. Detailed 3D stress analyses were required to ensure that the dovetails and the wheels meet design guidelines for the ATS turbine rotor.

Section 2.2.2.4.2 (GTFFTB) S3B and S4B Tip Shroud Design Optimization**Objective**

The objective of this task was to optimize stresses and creep deflections in the ATS third- and fourth-stage bucket shrouds. Detailed 3D creep analyses were needed to ensure that the stresses were within the required limits for creep life.

Plans

This task was completed in 3Q97.

Technology Application

The analysis performed in this task was incorporated into the shroud designs of the ATS gas turbine third- and fourth-stage buckets.

Section 2.2.2.4.3 (GTFFTB) Bucket Wide Grain Sensitivity Analysis**Objective**

The objective of this task was to show the effect on natural frequency of the variations in grain size and orientation of 9H fourth-stage buckets. If the variations in natural frequency could be shown to be non-critical, bucket yield would be improved.

Plans

This task was completed in 1Q97.

Technology Application

The results of this study were used on the ATS gas turbine design primarily as a means of improving bucket yield.

Section 2.2.2.4.3.1 (GTFFTB) Bucket Robust Design and Life Assessment**Objective**

The objective of this task was to use finite element analysis and Design of Experiments techniques to quickly estimate bucket life, identify optimized bucket critical-to-quality criteria (CTQs), and statistical distributions of bucket CTQs given statistical distributions of bucket parameters. The main reason for doing this work was to obtain robust bucket designs that are minimally sensitive to manufacturing tolerances and will therefore meet all life requirements.

Plans

This task was completed in 4Q97.

Technology Application

The results of this study were used on the ATS gas turbine in order to assess bucket performance and obtain optimized factor settings and statistical distributions of the CTQs given the distributions of the factors. The results of this study were used on the ATS gas turbine design primarily as a means of improving bucket yield.

Section 2.2.2.4.4 (GTETIH) Bucket Tip Treatment Heat Transfer**Objective**

The bucket tip regions of the ATS turbine remain a critical design issue affecting both turbine performance and life. Since the blades utilize no external film cooling, a tip design must be verified that minimizes both the tip hot gas leakage and the tip external heat loading, while also providing some shroud rub protection for the internal steam-cooling circuit. Standard squealer tip geometries are thought to provide inadequate rub protection and can be difficult to cool without film, while a plain tip geometry will not provide adequate leakage sealing.

This task continues design verification and design improvement for the first- and second-stage blade tips. A blade tip heat transfer cascade will be used with new or modified blade tip geometries to design and verify the appropriate tip heat transfer and seal arrangements in conjunction with manufacturing and cooling requirements. Specifically, this task will determine the external heat transfer coefficient distributions on the blade tip and on the airfoil surface near the blade tip using steady-state liquid crystal techniques in a blade tip cascade.

Plans

This task was completed in 4Q99.

Technology Application

The results from the testing performed under this task will be used directly in the design of the first- and second-stage bucket tips to improve tip performance and provide more accurate assessments of tip life. Tip geometries shown to have lower heat loads or less gap leakage, or both, will be incorporated into the design process.

Section 2.2.2.4.5 (GTFFTB) S1B and S2B Air/Steam Coolant Transition Analysis

Objective

The objective of this task was to determine the time required for switching from air cooling to steam cooling to keep thermal stresses in the ATS gas turbine first- and second-stage buckets within acceptable levels. Three-dimensional transient thermomechanical analyses of the first- and second-stage buckets were run during the transition from air to steam cooling. Predicted temperature and stress responses were used to evaluate the effect of the coolant change on the bucket life and to recommend control system modifications, if necessary.

Plans

This task was completed in 2Q97.

Technology Application

This analysis showed that air-to-steam transition requirements during startup will have to be controlled in order for the LCF life of the buckets to meet design guidelines.

Section 2.2.2.4.6 (GTETEH) S1B External Heat Transfer

Objective

The ATS turbine first-stage bucket is highly loaded both aerodynamically and thermally. It is crucial that the external heat loading for this component be predicted accurately. A non-conservative design heat load may result in a low life part design, while a too conservative heat load will lead to overutilization of steam coolant. As the heat load distribution is a major contributor to the bucket cooling design and its effectiveness, an accurate determination of the external heat transfer distribution is required to minimize the impact of other variable factors in the design.

This task provided external heat transfer coefficient distributions for the pitch section of the ATS turbine first-stage bucket. Cascade slave hardware was manufactured by CRD for installation into the Transonic Blade Cascade facility at NASA Lewis Research Center, Cleveland. NASA performed flow and heat transfer tests with a smooth airfoil and reported heat transfer distributions at the design Reynolds number. Rough surface testing was optional in this program. This task was carried out in conjunction with CRD's Research Alliance with NASA Lewis (no funds are exchanged in this Alliance).

Plans

This task was completed in 3Q98.

Technology Application

The results of this task were used to verify or alter the predicted design external heat loading for the first-stage bucket. Where the experimental results deviate significantly from the design predictions, changes in the blade coolant flow can be made to achieve a more efficient design.

Section 2.2.2.4.8 (GTETIH) S1B Leading Edge Turbulator Tests**Objective**

The serpentine cooling flow circuits of the first- and second-stage buckets of the ATS gas turbine have complicated flow configurations with 45° and 90° turbulators. Design flow analytical models include several empirical friction factors and heat transfer coefficients. A database for the leading edge passage of the serpentine circuit with 90° turbulators was developed by GEAE and GE Corporate Research and Development (CRD).

The objective of this task was to correlate friction factor and heat transfer coefficient data for leading edge passages with 90° turbulators. The accuracy of the correlations developed determined the need for additional tests with the 7H leading edge turbulated passage first-stage bucket geometry.

Plans

This task was completed in 4Q98.

Technology Application

The correlations developed will be incorporated into a database for leading edge passages with 90° turbulators that can be used in future design considerations. The additional friction factor data will improve confidence in the developed correlation.

Section 2.2.2.5.1 (GTFFTS) Turbine Stator Robust Design**Objective**

The objective of this work was to develop and apply robust design methods for the development of steam-cooled components of the advanced gas turbine. The goal of this effort was to achieve high standards of performance, quality, and reliability for these components by performing the following tasks during the product development cycle: (1) apply, and develop as needed, the robust design methodology to first- and second-stage nozzles; (2) apply the robust design methodology to some of the steam- and air-cooled stator components (e.g., first-stage shroud and turbine inner shell); (3) provide consulting and support for applying the robust design methodology to some of the

critical rotor components (e.g., manifold, steam tube bushings, and spoolie); (4) provide consulting and support for integration of design, manufacturing, and assembly; and (5) train the GEPS staff on the concepts, methods, and tools for achieving robust design.

A “robust design” is a design that satisfies the product performance requirements in an optimal manner and also exhibits minimal sensitivity to variabilities arising from various sources, such as manufacturing processes and tolerances, material behavior, operating environment, in-service damage, and maintenance and repairs. The methodology consists of the following key steps: (1) identification of critical-to-quality (CTQ) characteristics, key control parameters (KCPs), and key noise parameters (KNPs); (2) definition of the Design of Experiment matrices for KCPs and KNPs; (3) execution of the Design of Experiment matrices through analysis, testing, prototyping, and/or manufacturing; (4) statistical analysis of the Design of Experiment data to develop response surfaces, (5) optimization using response surfaces to determine optimal KCPs that meet the CTQ requirements and minimize sensitivity to variations; (6) performing Monte Carlo analysis to quantify the likelihood of meeting CTQ requirements under various noise conditions; (7) improving the part’s producibility and assembly by specifying wide manufacturing and assembly tolerances; and (8) validating the design developed through analysis and/or testing. The methodology was demonstrated successfully on a number of real-life complex applications and is being applied in the present project to steam-cooled components of the ATS gas turbines.

Plans

This task was completed in 4Q97.

Technology Application

Many results from these robust design studies were incorporated in drawing releases and are also being used to enhance the producibility of steam-cooled parts. Response surfaces are being utilized for assessing the LCF life of cast parts, and robust design methodology was applied by the design engineers to other components of the ATS gas turbine.

Section 2.2.2.6.1 (GTFFSTEF) Exhaust Diffuser Performance

Objective

The requirements for the ATS gas turbine exhaust diffuser include: (1) improved baseload pressure recovery performance compared with earlier GE exhaust diffuser designs and (2) operation without acoustic resonance at any operating point of the gas turbine. The objectives of this task were to test potential ATS gas turbine exhaust diffuser geometries for pressure recovery performance and to verify that the design selected did not excite acoustic resonances.

The test program included the installation and test of a scale-model diffuser with flowpath geometries and components compatible with the ATS gas turbine. Specifically, the cost-saving idea of internal insulation required axial ribs in the walls of the diffuser flowpath. Impact on pressure recovery was measured. Several other tests were performed, each with the aim of maximizing

performance. These tests included examining variations in flowpath, centerbody length and termination shape, steam pipe locations and fairings, and other diffuser features that affect performance. The final exhaust diffuser design was tested to verify that no acoustic resonances are excited, particularly at FSNL conditions.

Plans

This task was completed in 4Q97.

Technology Application

The results from this series of scale-model gas turbine exhaust diffuser tests were used to establish several diffuser design features, including the feasibility of an internally insulated exhaust frame, a less expensive option than external insulation. Data were used to design a diffuser with the required pressure recovery, enhancing the overall combined-cycle plant efficiency. These tests verified that the final design was free from acoustic resonances.

Section 2.2.2.6.2 (GTFFST) Steam Box CFD Analysis

Objective

The objective of this task was the design of a steam delivery system as part of the 9H/7H steam cooling design. A steam gland was designed to bring the cooling steam from a stationary inlet pipe onboard a rotating shaft. Steam entered the steam gland through an axial inlet pipe. The pipe turned 90° so that the resulting flow traveled tangent to the rotor shaft and into an inlet scroll. The inlet scroll cross-sectional area was sized to match the steam velocity to the rotor tangential velocity. As the steam traveled around the scroll circumferentially, some steam was extracted into rotor slots. A 3D CFD analysis was required to define the appropriate geometry of the steam gland inlet scroll that resulted in a nearly uniform radial outflow from the scroll circumference.

Plans

This task was completed in 4Q96.

Technology Application

The results of this study have had an impact on the design of the scroll geometry and confirmed its proper performance in meeting the desired uniform flow distribution. The analysis of the entrance to the rotor served three purposes: it incorporated rotational effects and confirmed the 1D analyses of the YFT study of the steam distribution system; it pointed to the relative insensitivity of the current design to variation in the inlet conditions of the flow; and, with the prediction of the relative swirl angle, obstacles in the annular passage were designed to be aligned with the incoming steam.

Section 2.2.2.7.1 (GTFFMS) Transient Gas Turbine Cycle Model

Objective

The objective of this task is to create a more detailed transient model of the flange-to-flange ATS gas turbine for use in the overall plant transient simulation. The plant simulation in turn is used to define the gas turbine internal boundary conditions for parts design and analysis and overall plant control strategies. A real time simulation is used to test the actual control for the ATS gas turbine.

Plans

This task was completed in 4Q98.

Technology Application

The plant transient model is used in the design of the ATS gas turbine control system as well as the overall plant control and equipment. Simulation results of contemplated equipment configurations and control strategies define the operating environment and design condition of the ATS gas turbine.

The safe and reliable operation of the ATS gas turbine is critically dependent on off-base systems whose actions do not necessarily follow or result from operation of the gas turbine. For instance, the pressure and temperature of the cooling steam supplied to the ATS gas turbine must be maintained within an allowable band to preserve hot parts life. These issues and many others, such as FMEA, are studied through use of the transient plant model.

The steam/gas process group combined cycle plant transient simulation requires a model that has good fidelity with the steady-state ATS gas turbine cycle model and a reasonable computer execution time. The combined cycle model is used to define overall plant control strategies and design conditions for plant and balance of plant equipment. The simulated operation of the ATS gas turbine and its control within the overall plant then provides information on transient design conditions for the design of the gas turbine itself. The current transient model runs on a PC with the OS2 operating system using the PC-Trax program.

The controls design group requires a real time ATS gas turbine transient cycle model with an accuracy of $\pm 1\%$ of the steady-state cycle model. The requirement for a real time transient model is due to the need to connect the computer model input/output electronically to the ATS gas turbine control for design and checkout. The real time requirement means that the model calculation time must be less than the sampling time of the actual control.

Section 2.2.3.1 (GTETNC) S1N Design**Section 2.2.3.1.1 (GTETNC) Nozzle Cascade CFD Analysis****Objective**

The objective of this task was to apply a fully viscous 3D CFD analysis to predict the flow and aid in the generation of heat transfer boundary conditions for the first-stage nozzle cascade test. Such a validated CFD tool then became the vehicle to apply the nozzle cascade test data to the actual machine design problem.

Plans

This task was completed in 1Q96.

Technology Application

The validation of NOVAK3D predictive capabilities provided a valuable tool to evaluate the impact of design modifications and off-design performance of ATS nozzles in particular. It also contributed to a more realistic calculation of heat transfer coefficients and consequently enhanced the heat transfer predictions in complex geometries.

Section 2.2.3.1.2 (GTETEH) Combustion-Generated Flow Effects on Heat Transfer**Objective**

The objective of this task was to evaluate the freestream turbulence intensity incident upon the ATS first-stage nozzle airfoil, and the effect of this turbulence level on the airfoil heat load. This turbulence intensity level and its character have a major and direct bearing on the heat load for the nozzle airfoil and endwall.

Plans

This task was completed in 4Q96.

Technology Application

The ATS nozzle cascade test results were incorporated directly into the ATS first-stage nozzle design. Comparison of results with both high-turbulence-generating perforated plates and a DLN combustor system cold-flow mockup verified the applicability to design of heat transfer results from the former method.

Section 2.2.3.2 (GTETRS) Rotor Steam Transfer

Objective

For stable cooling of the turbine buckets, static flow tests will be conducted to validate the steam flows in the circuit to and from the buckets, through the rotor. These will establish flow losses for the unique components in the steam delivery circuit.

Plans

This was completed 4Q99.

Technology Application

Rotor steam transfer tests are used to evaluate the design optimum for the 7H and 9H turbine bucket cooling.

Section 2.2.3.3 (GTETSE) Spoolie Test Program

Objective

The primary seals in the H machine are tube seals (spoolies), which are needed to accommodate misalignment between the components due to tolerance stack-up and thermal growth in the rotor steam circuit. The leakage through these seals is expected to change over the life of the H machine and thus have a significant effect on its performance. For example, an initial improvement in sealing ability is expected as the mating surfaces seat themselves. This sealing ability is then expected to degrade with increased wear of the seals. Additionally, cyclic centrifugal loading due to turbine startup and shutdown is expected to cause fatigue cracks that can significantly increase leakage.

The objectives of this task are (1) to validate the design of the spoolie by determining the leakage rate as a function of wear and fatigue and (2) to determine the design and service factors that have the strongest effect on leakage through the spoolie.

Plans

This task was completed in 4Q99.

Technology Application

The results of this task will be used to predict spoolie life and performance in service. In addition, failure analysis will help improve spoolie design through use of superior materials and design parameters.

Section 2.2.3.4 (GTETRH) Rotational Heat Transfer

Section 2.2.3.4.1 (GTETRH) Rotational Effects on Bucket Mixing Ribs

Objective

The addition of mixing ribs to turbine blade radial cooling passages was found to provide a more robust thermal design, without the severe reduction in performance measured previously, when evaluated in sub-scale models at low Reynolds numbers. Since this design improvement is scheduled for use in the ATS gas turbine, design data that incorporate this change need to be obtained at full-scale conditions in the operating range of interest.

A full-scale turbulated test passage of the appropriate aspect ratio was constructed that was identical to the one tested previously except for the addition of the new mixing rib geometry. This passage was evaluated in the full-scale rotational test rig over the range of dimensionless parameters present in the ATS gas turbine.

Plans

This task was completed in 1Q98.

Technology Application

The new turbulator and rib design, which had been demonstrated previously only in small-scale tests, was employed to reduce the bucket cost and to yield a more robust design with improved performance at high Buoyancy numbers. This design was validated by the full-scale data generated under this task.

Section 2.2.3.4.2 (GTETRH) Bucket Cooling Circuit Rotational Pressure Drop Test

Objective

The objective of this task was to determine the effect of rotation on the pressure drop in a radial bucket cooling passage. The CFD computations of the effect of rotation on bucket cooling passage heat transfer and pressure drop indicated a significant effect of the Buoyancy number on pressure drop. Since the bucket pressure drop is a major fraction of the total system pressure drop involving the coolant, it was deemed necessary to measure this effect using the full-scale test rig.

The high aspect ratio turbulated duct assembly was instrumented to measure the pressure drop between the inlet and outlet manifolds. Appropriate heaters were employed on the pressure measurement lines to avoid condensation of the working fluid and to minimize the density corrections required due to temperature differences between the measurement lines and the test duct. This allowed the differential pressure transducer to be mounted near the rotational axis, where no transducer correction for centrifugal effects was required. The pressure drop for both outflow and radial inflow was measured.

Plans

This task was completed in 3Q96.

Technology Application

The new pressure drop correlation, which includes the effect of the Buoyancy number, is now in use in the evaluation of alternate coolant passage designs and in the evaluation of the flow-pressure drop characteristic of the ATS turbine bucket cooling system.

Section 2.2.3.4.3 (GTETRH) Rotating Trailing Edge Heat Transfer Tests**Objective**

As reported in Section 2.2.3.4.1, a number of tests were conducted to measure the heat transfer coefficients in the cooling passages of buckets. The completed tests focused on rectangular turbulated ducts (some with mixing ribs) of various aspect ratios representative of the range of geometries of cooling passages in most of the cooling circuit. The trailing edge cavities of the buckets, however, have a more triangular shape, and also have the difficult task of cooling the trailing edge. Validation of the ATS gas turbine second-stage bucket trailing edge passage is required primarily because of the strong effect of rotation on radial outflow, but also because of geometrical differences. The objective of the current task was to measure the heat transfer coefficients in a constant-area duct that captures all of these features. Tests were performed in the full-scale rotational test rig.

Plans

This task was completed in 4Q98.

Technology Application

Results from these tests will be used to update cooling heat transfer boundary conditions for stress and life calculations for the second-stage bucket, and will also be used to reassess the heat transfer coefficients used in the first-stage bucket trailing edge cavity.

Section 2.2.3.5.1 (GTETS2NHT) S2N Trailing Edge Flow Test**Objective**

The objective of this task was to perform heat transfer tests in the trailing edge region of the second-stage nozzle using a Plexiglas™ model built in 1995. The purpose of the work was to generate a cooling scheme that will (1) even out the coolant side heat transfer coefficients along the channel and (2) yield results that are comparable to or better than the turbulent pipe flow correlation predictions.

The model kept the important geometric variables of the passage close to the actual design. It had thin-foil heaters on both the suction and pressure sides, and liquid crystals to determine the

temperature distributions. Tests were planned to investigate the triangular passage performance with several turbulator designs.

Plans

This task was completed in 3Q96.

Technology Application

The test results for cooling passages in the second-stage nozzle trailing edge cooling circuit provided the necessary design information and turbulator configurations for the ATS second-stage nozzle. This allowed the design to obtain the desired heat transfer enhancement for the passages and to channel the cooling flow near the apex of the triangular flow passage near the trailing edge region effectively.

Section 2.2.3.5.2 (GTETIH) S2B Trailing Edge Heat Transfer Tests

Objective

The initial task objective was to provide adequate experimental data to verify the performance of the second-stage bucket trailing edge cooling circuit. Because film cooling and trailing edge bleed cooling are incompatible with the ATS gas turbine objective of closed circuit cooling, the bucket trailing edge must be cooled completely by convection in the trailing edge cavity. The geometry and flow conditions in the trailing edge cavity are different from any analyzed and tested previously. The heat transfer coefficients in the cavity are determined experimentally using a scale model. The experimental results are used to guide and improve the design of the bucket.

The trailing edge tip turn region will get specific attention in order to optimize its design. The objective here is to determine the heat transfer coefficients within the second-stage bucket trailing edge tip turn region for the current design, and to modify and test the geometry for longer life design. Modification will include re-positioning of the internal flow turning vane, resizing of the vane, or reshaping the casting to produce a turning flow passage internally. An existing liquid crystal test model of the region will be used in stationary testing. If required, a CFD model will also be run to account for the effects of rotation.

The current objective of this task is to verify detailed predictions of flow distribution in the trailing edge cavity of the second-stage bucket. Measurements will be made at numerous static pressure taps in the trailing edge cavity and the cavity immediately downstream of the trailing edge cavity. These data will be used to refine the 1D flow models used to predict internal bucket cooling flows. Measurements are being made on a 2X model of the trailing edge tip-turn region, a 1X casting of a whole bucket, and 1X castings of individual trailing edge cavities.

Plans

This task was completed in 3Q99.

Technology Application

The results of this task will be used to validate design predictions for the internal tip-turn region of the second-stage bucket trailing edge. Detailed local heat transfer coefficients will be obtained for a more precise assessment of component cooling in this area. The test model will also provide a vehicle to optimize the internal steam cooling in this tip region with minimal impact on the overall second-stage bucket design. The results of this task will also be used to validate design predictions of internal cooling flow distributions and heat transfer for the trailing edge region of the second-stage bucket.

Section 2.2.3.5.3 (GTETIH) S1N Outer Band Liquid Crystal Heat Transfer Tests**Objective**

The objective of this task was to perform heat transfer tests with a representative outer band impingement configuration and measure the heat transfer coefficient distributions underneath the impingement jets. The data were compared with the design calculations and expectations. A test rig was used to simulate the design impingement jet plate geometry as closely as possible. The test section walls were instrumented with three etched thin-foil heaters and a liquid crystal layer to measure the local wall temperature distributions as a function of flowrate and heat flux. The temperature data were then converted into heat transfer coefficient values.

Plans

This task was completed in 4Q96.

Technology Application

The test results obtained with the flow and heat transfer tests showed that the design calculations and models were able to successfully predict the flow directions and heat transfer coefficients for the complicated impingement pattern of the ATS first-stage nozzle outer band. The tests also showed that the heat transfer is dependent on the leading and trailing edge cavity discharge pressure levels. In addition, the data showed that an impingement design without a separating rib is more effective than a design with a separating rib on the suction and pressure sides.

Section 2.2.3.5.4 (GTETIH) S1N Convex Cavity Heat Transfer Tests**Objective**

The objective of this task was to perform flow and heat transfer tests in a simple test rig representative of a first-stage nozzle convectively cooled passage geometry with two different turbulator designs to determine the effect of corner radius on the heat transfer enhancements

obtained with the turbulators. Two simplified plastic models of the cooling channel were constructed with the important geometric variables kept as close as possible to the actual design. An additional test section was also constructed to model the exact geometry of the convectively cooled cavity, which incorporated the area changes along the radial distance. The inside surfaces of the test pieces were coated with liquid crystal paint or a liquid crystal sheet, and transient and steady-state tests were run to determine the friction factors and local heat transfer coefficient distributions. The results were also compared with the CRD database. An additional flow test was conducted with a metallic test section manufactured with exactly the same dimensions as the prototypical passage to verify the flow models of the design.

Plans

This task was completed in 4Q96.

Technology Application

The results of these tests with rectangular and filleted turbulated tubes provided the designer with information on the differences between the two and showed that the database can be used to predict the friction and heat transfer. The results with various turbulator heights led to a change in the design requirements to prevent large variations in the local heat transfer coefficients. The test data also showed that the heat transfer enhancements are not reduced at the high Reynolds numbers of interest for the present design.

Section 2.2.3.5.5 (GTETIH) Bucket Tip Closed Circuit Cooling

Objective

The objective of this task was to measure non-rotating heat transfer and pressure drop in the 180° tip-turn region of a two-pass serpentine bucket tip, and to evaluate the ability of an enhanced surface in the tip region to enhance the tip cooling without a substantial pressure drop penalty.

Plans

This task was completed in 3Q96.

Technology Application

These results were used by the designers of the ATS gas turbine buckets to design the tip-turn regions of serpentine cooling circuits.

Section 2.2.3.5.6 (GTETLE) Bucket Leading Edge Heat Transfer Testing**Objective**

The objective of this task was to evaluate turbulator geometries for the first-stage bucket leading edge passage by performing non-rotating heat transfer and pressure drop tests at high Reynolds numbers on scaled models of the leading edge passage.

Plans

This task was completed in 4Q96.

Technology Application

The heat transfer and pressure drop results from this task were used in the design of the first-stage bucket in the ATS gas turbine.

Section 2.2.3.5.7 (GTETIH) S1N Surface Enhanced Internal Heat Transfer**Objective**

The objective of this task was to investigate and determine the heat transfer coefficient enhancements that could be generated under impingement jet cooling modules by adding surface roughness elements without increasing the total system pressure drop. The effect of bumps missing in some regions due to manufacturing problems was also investigated.

The test section used for impingement heat transfer tests was enclosed in a high-pressure enclosure that could be operated at pressures up to 10.2 atm (150 psia) by means of a back-pressure control valve. The impingement air was fed to a supply chamber equipped with a square impingement jet plate that could accommodate several hole configurations. The impingement test surface was in intimate contact with a copper block heated by four cartridge heaters. The impingement test plates, positioned at a controlled distance from the impingement jet plates, were instrumented with four embedded thermocouples that measured the plate temperature. Tests were conducted at various jet Reynolds numbers and several jet plate geometries. To investigate the effect of bumps missing in some regions, the high-pressure containment was modified so that a window could be attached at one end. A thin-foil heater and a liquid crystal assembly were glued onto the impingement test plate and the color changes observed with the liquid crystal video thermography (LCVT) system.

Plans

This task was completed in 4Q96.

Technology Application

The ANSYS analysis results provide the increases in wall temperature expected for various numbers of bumps missing. The acceptable temperature rise will determine the quality control

criteria and the nondestructive testing technique for the missing bump number determination. The transient technique provides a nondestructive technique to check the non-uniformity of the cooling and the number of missing bumps. Section (GTETBKHT) High Reynolds Number Turbulator Static Heat Transfer Test.

Section 2.2.3.5.8 (GTETIH) S1N Trailing Edge Heat Transfer Tests

Objective

The first-stage nozzle trailing edge triangular cavity is air-cooled and uses a combination of several cooling techniques. The turbulated main passage feeds several trailing edge slots whose heat transfer is enhanced by pin fins and high solidity turbulators. Rows of film cooling holes are also provided from the tip to the root sections of the airfoil to enhance the cooling effectiveness and provide adequate cooling where necessary. The flow and heat transfer inputs for the design are complex and need verification testing. Information in the open literature shows that the film hole discharge coefficients depend on the supply side velocity (Mach number) and orientation of the film holes with respect to the supply cross flow.

The objective of this work was to build a representative model of the trailing edge cavity and measure the film discharge coefficients as a function of the feed flow Mach number and the pressure ratio across the film holes.

An additional focus of this task related to nozzle trailing edge heat transfer is the performance of the trailing edge cooling passages.

Short, partly turbulated STEM-drilled passages are being used to cool the trailing edge of the first-stage nozzle. Since the inside diameters of these passages are relatively small (0.040 to 0.060 inch) they are outside of the CRD database. The STEM-drilling process results depend on the base material processed. Two vendors have been manufacturing these STEM-drilled passages. The objective of this subtask is to have each vendor manufacture a STEM-drilled passage so that the friction factors and heat transfer coefficients can be determined and compared.

Plans

This task was completed in 4Q99.

Technology Application

The friction factor and heat transfer results obtained with the turbulated low aspect ratio passage will check the design tool predictions and form the basis for parametric evaluations. The testing of new concepts will verify the design assumptions with respect to the pressure drop and heat transfer coefficients.

The friction factor and heat transfer information generated with these two new tubes will provide design information for these trailing edge tubes, and will generate complementary information to the existing design database. Visual observations of the turbulators will also allow a comparison between the process capabilities of the two vendors.

Section 2.2.3.5.9 (GTETBKHT) High Reynolds Number Turbulator Static Heat Transfer Test

Objective

The objective of this task was to investigate and determine the heat transfer coefficient enhancements possible in the first-stage nozzle. Internal cooling was supplied by two different types of convection: one using impingement heat transfer within the internal airfoil cavities, the other using high Reynolds number turbulated heat transfer within the aftmost convective channel of the airfoil. This task concentrated on the latter type of heat transfer. Experimental work reported in the open literature on turbulator heat transfer enhancement and friction factors is limited to passage Reynolds numbers below 80,000. This task supplied data and correlations that were used for advanced machine design conditions. Heat transfer and pressure drop data were required at far higher Reynolds numbers than previously tested with common turbulator geometries and passage aspect ratios.

Plans

This task was completed in 4Q96.

Technology Application

The results from this task were applicable to any non-rotating components in the ATS gas turbine that used turbulated passages for cooling. As long as rotational effects were accounted for, these results were also applicable to turbulated passage cooling of rotating components.

Section 2.2.3.5.10 (GTET) Impingement Degradation Effects

Objective

The internal nozzle design verification tests conducted in 1996 with various impingement jet plates and test plates showed that the impingement heat transfer coefficients measured under the first and second rows of the impingement jets were lower than the open literature correlation predictions (Metzger). Although this difference was not significant in some regions, it was important in others where accurate knowledge of the heat transfer coefficients under the first two impingement jets is important. The differences between the design verification test results and the correlation predictions were attributed to the fact that in those tests the first row of jets was near a wall with zero velocity boundary conditions while in the correlation tests the first row was adjacent to a constant pressure boundary condition.

The objective of this task was to understand the physical phenomenon that causes the observed difference. The local static pressure distributions along the cross flow regions of the impinging jets were measured for two inlet boundary conditions, one with a wall and the other with a constant pressure. Tests were also conducted with the cross flow discharging in one direction across the impingement jets and discharging in two directions symmetrically from the center row.

Plans

This task was completed in 3Q97.

Technology Application

The results obtained clarified the discrepancy between prior test results and results from open literature correlation predictions (Metzger). The new data improved the design of the first-stage nozzle internal cooling scheme.

Section 2.2.3.5.13 (GTETIH) S1N and S2N Endwall Heat Transfer

Objective

Additional high Reynolds number impingement heat transfer data with brazed microturbulator-roughened enhanced surfaces are needed for possible application to the first- and second-stage nozzle outer and inner sidewalls.

Plans

This task was completed in 3Q99.

Further testing is required and will be wrapped into testing of the edge cooling included in Section 2.2.3.5.12 of this document.

Technology Application

The heat transfer information generated will be used in the cooling design of the inner and outer sidewalls where the cast bumps could be replaced with the brazed micro-turbulators.

Section 2.2.3.6 (GTETEH) Surface Roughness and Combustor-Generated Flow Effects on Heat Transfer

Objective

The effects of TBC surface roughness on external heat transfer were characterized using flat plates tested in an atmospheric wind tunnel. An advantage of flat plates over airfoils is that TBCs can be applied easily and polished to uniform thickness and surface finish. Full mapping of the TBC surface topography was performed to support infrared mapping of the surface temperatures (heat transfer coefficients). Reynolds numbers spanned those expected in the ATS turbine inlet nozzle surface

away from the leading edge. Tests included plates with and without leading edge step heights to model the effects of component interface misalignments. Verification tests on airfoil replicas were also performed.

Plans

This task was completed in 4Q97.

Technology Application

Application of the data obtained from this task takes two forms in the design of the turbine airfoils. First, tests that measure the effect of TBC surface roughness on external heat transfer were used to determine the extent of necessary polishing for new parts. Second, detailed quantification of the heat transfer magnitude associated with actual TBC roughness allowed for more accuracy in the initial design of airfoils. The data obtained on flowpath steps were used directly in the design of the turbine nozzle sidewalls to assess the impact and consequences of heat transfer enhancement due to steps, including the effect of TBC roughness as a possible mitigating factor.

Section 2.2.3.6.1 (GTETEH) S1N Heat Transfer for Production Aero with TBC Spall Effects

Objective

The objective of this task was the quantification of the external heat transfer coefficient distribution for the production aerodynamic design definition of the ATS turbine inlet nozzle airfoil.

A previous task begun in Phase 2 and completed under Phase 3 quantified the external heat transfer distributions for the original aerodynamic design, including effects due to roughness and turbulence intensity. The production aerodynamic design was sufficiently different in crucial regions to warrant a new series of tests, again including roughness and turbulence intensity effects. The new aerodynamic definition for the nozzle was specifically designed to lower the heat load on the airfoil. Results from the previous cascade tests were used on the new airfoil design, but with the assumed validity of local Reynolds number scaling of heat transfer coefficients. Since such scaling of results had no experimental basis for airfoils that deal with complex flows, it was necessary to verify the new design. Results from the original series of tests were used to reduce task efforts to a minimum. Most of the original apparatus hardware from the ATS turbine inlet nozzle cascade was reused for this task.

Plans

This task was completed in 1Q97.

Technology Application

The results from this series of tests yielded external heat transfer load validation on the production first-stage nozzle design.

Section 2.2.3.6.2 (GTETEH) Surface Roughness Effects on Heat Transfer

Objective

The external heat loading for the ATS first-stage nozzle airfoil was heavily dependent on the nonlinear effects of surface roughness, especially as the nozzle design could not rely on film cooling. Given the current state of turbine cooling technology, the only viable method for determining the nozzle heat load with roughness effects was experimental validation of the heat transfer distribution under non-dimensional engine-representative conditions.

The ATS turbine inlet nozzle cascade was used to provide data on external heat transfer coefficients on airfoils with surface roughness. The cascade incorporated instrumented airfoils with flow conditions representative of the ATS inlet nozzle geometry. The appropriate non-dimensional parameters for dynamic similarity were close to those of the engine inlet nozzle. External heat transfer coefficient distributions were measured through the use of embedded thermocouples, with a constant surface heat flux condition supplied by thin-foil heaters. Surface roughness elements of the appropriate size and distribution were bonded onto the surface heaters. Data included various roughness levels, distributions, and types to allow the calibration of predictive methods. Characterization of surface roughness effects included the interactive nature of roughness with fluid dynamic conditions such as acceleration. The cascade was also used to assess the effects of transition piece wake shedding on airfoil heat transfer, the effect of extreme surface roughness representative of as-sprayed thermal barrier coatings (TBCs), and the effect of modeled coating spallation on heat transfer enhancements.

Plans

This task was completed in 3Q96.

Technology Application

The test results were used directly in the design of the ATS first-stage nozzle airfoil. Thus the cascade conditions for an appropriate rough surface condition, with elevated freestream turbulence intensity from a DLN combustor mockup, were used as the convective heat load definition for the nozzle airfoil. Since modeled spallation heat transfer enhancements were equal to or below the assumed enhancement levels for the nozzle design, the conservative nature of this portion of the design was verified. Cascade testing verified the requirement to polish the thermal barrier coating on the full-scale nozzle cascade instrumented airfoils, thereby avoiding potential test problems in that task. The optimal relative location for the transition piece endwall segments, as determined through cascade testing, was incorporated into the turbine design.

Section 2.2.3.7 (GTETCP) LCF Coupon Tests**Section 2.2.3.7.1 (GTETCP) LCF and Crack Propagation Rate Tests****Objective**

The E-beam high thermal gradient test facility will be used to test several nickel-based superalloy (N5) coupons for LCF durability. The coupons will be geometrically representative of a section of the turbine inlet nozzle airfoil containing hot and cold sides. Coupons will be instrumented for the evaluation of thermal conditions during testing. Tests will be performed to evaluate metal durability under conditions of temperature, thermal gradient, and stress representative of the ATS turbine inlet nozzle. Testing will be cyclic, developing cycles of exposure on the test coupons considered representative of engine cycles. Post-test evaluations of the TBC and metal conditions will be performed. Data will provide a basis for LCF life evaluations.

In addition to the high thermal gradient testing of superalloy coupons for LCF durability, this task will also assess the crack propagation rate of N5 in the presence of steam. This will be done in two ways: (1) isothermal, mechanically loaded testing of tubular specimens through which steam is passed and (2) high thermal gradient testing of a tophat specimen in the presence of steam. Post-test evaluations of the metal conditions will be performed. Data will provide a basis for LCF life.

Plans

This task was completed in 3Q98.

Technology Application

The results of the tests conducted as part of this task were used as a basis for LCF life evaluation of the first-stage nozzle and first-stage bucket for the ATS gas turbine.

Section 2.2.3.8 (GTETSP) Steam Particulate Deposition**Section 2.2.3.8.1 (GTETSP) Steam Cooling System Cleanliness****Objective**

One initial objective of this task was to measure the rate and location of steam particulate deposition in bucket tip-turns and in two heat transfer structures to be employed within the ATS gas turbine nozzles and buckets. The information was to be translated into a steam purity specification and full-filter specification for the ATS gas turbine. The approach employed was to use gas turbine combined cycle (GTCC) steam flowing in series through a special filter specified for the ATS gas turbine, then through the tip-turns in a specially constructed centrifugal deposition rig, and finally through two static specimens consisting of turbulated and impingement-cooled specimens. Amounts and locations of deposits in these specimens were used to verify the predicted time-between-outages (TBO) results from ATS Phase 2 studies.

The ATS gas turbine cooling system cannot be chemically cleaned like a boiler because of the number of unwelded joints (e.g., spoolie/tube joints, interference fits) where chemicals could concentrate and create corrosion and wear problems. This task explores the possibility of flushing the system with clean water, clean air, or some combination of the two not only to provide increased cleanliness assurance of subassemblies, but also to move contamination away from critical surfaces (especially bucket tip-turns) when the engine is off-line. A measurement technique will be developed for coolant duct surface cleanliness for use on the assembly floor. Effort will also be focused on developing procedures for flushing the assembled cooling circuits at assembly and, if possible, when the engine is fully assembled but off-line.

Plans

This task was completed in 4Q99.

Technology Application

Output of this task has contributed to the identification, experimental validation, and specifications for the on-line filter system ordered from the vendor for the first plant. The experimental program also provided the first-hand experience necessary to provide consultation on issues of condensate measurements and feedwater treatment systems. The development of the surface cleanliness measurement was quickly transitioned to the factory floor where it is now in use providing go/no go decisions on whether parts are sufficiently clean to proceed with assembly. The successful demonstration of an ability to flush the cooling system components will reduce remnant contamination at first fire, and it will also assure that contamination will not limit time between outages for engine disassembly.

Section 2.2.4.2 (GTMTSO) Oxidation Due to Steam

Objective

Testing of ATS materials in steam will be performed to evaluate the long-term oxidation responses to this environment. Specimens will be subjected to steam exposure in an autoclave and removed at specified intervals for examination of oxidation characteristics.

Plans

This activity was completed in 4Q96.

Technology Application

This task will evaluate the static behavior of turbine materials in a steam environment in order to account for the introduction of steam cooling.

Section 2.2.4.3 (GTMTCE) Corrosion Rate Evaluations of Airfoil Overlay Coatings**Objective**

The objective of this task is to evaluate the performance of ATS materials in potentially corrosive environments with various overlay coatings and substrate materials. Initial evaluations will be performed in small burner rigs with known contaminants. This will allow ranking of the corrosion rates of materials and coatings. Subsequent testing will be performed in facilities that better simulate gas turbine service conditions, including high gradients, for confirmation of burner rig results.

Plans

This activity was completed in 4Q97.

Technology Application

This task will evaluate potential airfoil coatings in environments that reflect planned turbine operating conditions.

Section 2.2.4.4 (GTMTBV) Compressor Blades and Vanes Materials and Processes**Objective**

Although material selections have been completed, this task will examine potentially less expensive materials for use in blades and vanes in the latter stages of the ATS compressor. These evaluations of alternate materials will be based on results of tests of mechanical properties, with emphasis on high cycle fatigue properties. For materials that have been selected, tests of critical properties will be conducted under ATS-specific conditions. Component tests of select parts will be conducted for life verification purposes and establishment of final manufacturing parameters.

Plans

This activity was completed in 1Q97.

Technology Application

This task will characterize the mechanical behavior of existing and new blade/vane materials in more aggressive environments than past compressor operation.

Section 2.2.4.5 (GTMTVG) Compressor Variable Guide Vane System Design Support and Process Development**Objective**

Information to support selection of materials for the variable guide vane bushings and thrust washers will be gathered to ensure a robust and reliable design. Testing will be conducted to confirm

materials selections, cover any parameters outside of existing data, and gather data for new materials.

Plans

This activity was completed in 2Q97.

Technology Application

This task will provide operational test data on ancillary materials used in the variable guide vane system. Potential bushing and sleeve materials will be screened.

Section 2.2.4.6 (GTMTCS) Compressor Structural Materials and Processes**Objective**

Mechanical and physical property tests will be performed on ATS compressor structural materials to provide an expanded mechanical and physical property database for design validation and enhancement. Material processing parameters for prototype manufacturing of the components will be selected based on design requirements and discussions with vendors. When necessary, material and processing specifications will be modified, or new ones written.

Plans

This activity was completed in 3Q99.

Technology Application

This task will continue characterization of compressor structural materials in test conditions that reflect service environments.

Section 2.2.4.7 (GTMTRF) Turbine Rotor Forging Materials and Processes**Objective**

Processing parameters of forged large turbine rotor components will be optimized to achieve the desired forging attributes. These parameters include chemistry and processing temperatures as well as post-processing surface treatments. Sub-size and full-size forgings will be produced to verify and evaluate the processing approaches, and forging supplier process plans will be developed for all components. Forging acoustic properties will be determined by ultrasonic testing on test block and prototype parts. The attenuation, anisotropy, frequency bypass, and signal-to-noise ratio will be measured and used in fracture mechanics analyses to support rotor design. Optimized inspection methods, any necessary software, and scan plans will be developed based on the work with prototype parts. Property evaluations will be conducted to ensure that material behavior models used for design accurately reflect those achieved in parts made by the manufacturing process selected.

Plans

This activity was completed 4Q99.

Technology Application

This task will enhance process capabilities for manufacture of turbine rotor forgings.

Section 2.2.4.8 (GTMTRS) Turbine Rotor Spoolies and Transfer Devices Materials and Processes**Objective**

Although material selections for the cooling system delivery systems have been completed, this task will perform testing to verify properties and identify potentially better materials. Any applicable or needed coatings or joint materials will also be identified. Procedures for joining delivery components together and inspecting them will be evaluated.

Plans

This activity was completed in 4Q99.

Technology Application

This task will develop processes and mechanical property data to optimize steam delivery hardware manufacture and subsequent operation.

Section 2.2.4.9 (GTMTSB) Structural Bolting**Objective**

Mechanical and physical property tests on two high strength bolting materials will be conducted at ATS turbine conditions. If required, manufacturing trials will be conducted to optimize forming processes.

Plans

This activity was completed in 1Q98.

Technology Application

This task will increase the database for flange/flange and wheel/wheel bolting applications.

Section 2.2.4.10.1 (GTMTTA) Airfoil NDE**Objective**

The objective of this task is to apply advanced methods of nondestructive evaluation (NDE) and metrology for the quality assurance of various airfoils of the ATS gas turbine. Critical NDE and metrology requirements for the ATS gas turbine airfoils include detection of internal casting defects in the walls of first stage bucket and nozzle airfoils, measurement of the wall thickness in the single-crystal and directionally-solidified ATS gas turbine airfoil castings, and inspection of the cover-to-nozzle welds in the ATS gas turbine nozzle assemblies.

Plans

This task was completed in 4Q99.

Technology Application

The design requirements and advanced nickel alloys used in the hot gas path airfoils for the ATS gas turbine require enhanced inspection methods to assess component quality. The NDE and metrology methods emerging from this task will be integrated into the overall quality assurance program for the ATS gas turbine airfoils to provide the necessary data to the design staff for more accurate lifing predictions for critical ATS gas turbine airfoils.

Section 2.2.4.11 (GTMTCB) Combustion Materials and Processes**Objective**

Properties of materials for combustion components will be evaluated at ATS conditions.

Plans

This activity was completed in 4Q97.

Technology Application

This task will enhance processes and mechanical property data to optimize combustion hardware manufacture and subsequent operation.

Section 2.2.4.12 (GTMTST) Turbine Structures Materials and Processes**Objective**

Producibility evaluations for the turbine structures will include selection of materials processing parameters and chemistry, and preparation of material and process specifications. Processing trials will be used to confirm producibility and verify capabilities of suppliers. Testing will be conducted where necessary to evaluate the materials under ATS conditions.

Plans

This activity was completed in 4Q97.

Technology Application

This task will continue characterization of turbine structure materials in test conditions that reflect service environment.

Section 2.2.4.13 (GTMTSH) Turbine Shells**Objective**

Materials and processes will be identified for production of the turbine shells. Specifications will be defined after material property testing and process verification/optimization trials are conducted to achieve the best quality part to meet all design criteria.

Plans

This activity was completed in 4Q97.

Technology Application

This task will enhance characterization of turbine shell materials in test conditions that reflect service environments.

Section 2.2.4.14 (GTMTSR) Seal Technology**Objective**

Improved gas path seals will be developed for the ATS turbine utilizing seal technology developed for aircraft engine components, where applicable. The technology will be evaluated utilizing developmental hardware and samples.

Plans

This activity was completed in 4Q96.

Technology Application

This task optimized seal attachment processes focused at airflow leakage restrictions to enhance performance.

Section 2.2.4.14.1 (GTFFTSSESV) Hot Gas Path and Transition Piece Cloth Seals**Objective**

Seals between the hot gas path turbine components are required to help meet the ATS combined cycle efficiency target. One objective of this task was to develop and test hot gas path seals that meet both leakage performance and life requirements. Specifically, improved sealing performance that reduces the equivalent gap of the seal was sought by replacing the current Q-tip seals with a cloth sealing system. The cloth seals also need to meet the same full-life requirement.

Seals between the combustor transition piece and the first-stage nozzle were required to help meet the ATS combined cycle efficiency target. The other objective of this task was to develop and test transition piece cloth seals that met both leakage performance and life requirements. Life consistent with the prescribed inspection interval is required.

Plans

This task was completed in 4Q97.

Technology Application

A turbine stator (shroud) is built up of several annular segments that are packed together at circumferential and axial junctions. The junctions between these segments need to be sealed in order to minimize leakage and maintain high efficiency. Typically such junctions have slots on the mating edges. Seals are used in the slots, bridging adjacent members, to block off any leakage. Current turbine designs do not have any seals for the curved circumferential junctions. Straight axial junction (dogbone) seals are used in some newer machines. Cloth seals provide the capacity to reduce seal leakage significantly.

Section 2.2.4.14.2 (GTETBS) Steam Gland Brush Seals**Objective**

Brush seals were developed to minimize steam leakage in the steam gland. Leakage reduction increased the efficiency of the ATS gas turbine. The successful implementation of brush seals in the steam gland also allowed for a reduction in the axial length of the steam gland. The shorter length will result in a manufacturing cost reduction.

Plans

This task was completed in 4Q97.

Technology Application

The data obtained from this task will be used to help specify design requirements for steam gland brush seals on the ATS gas turbine.

Section 2.2.5.2 (GTTTRR) TBC Risk Reduction

Objective

TBC durability will be evaluated under conditions very similar to the surface temperature, thermal gradient, and stress state of TBCs on ATS gas turbine components. An electron-beam rig capable of inducing high thermal gradients will be used to assess the relative durability of various TBCs, and the controlling mechanisms of TBC failure will be characterized. TBCs with a spectrum of microstructures will be tested. The effects of environmental contaminants on TBC performance in high thermal gradient conditions will be investigated. Numerical modeling will be used to determine the stress, strain, and thermal gradient conditions in the various TBCs during the tests.

TBC-coated nozzles tested in the ATS Turbine Nozzle Cascade rig will be evaluated following completion of cascade testing.

Plans

This task was complete 4Q99.

Technology Application

Durability of the baseline TBC system in an environment simulating that of the ATS turbine will be evaluated. These results will establish confidence that the TBC will provide acceptable minimum durability for safe and reliable operation of the ATS turbine within the time frame of the first inspection interval.

Section 2.2.5.3.1 (GTFFTB) Bucket TBC Roughness and Spall Characterization

Objective

This task quantified the external airfoil heat transfer coefficients associated with the roughness characteristic of TBCs. Special attention was paid to the roughness associated with TBC structure, which can be very different from that of metallic surfaces or coatings.

Typical average roughness measurements made on surfaces cannot fully distinguish between metal finishes, artificial rough surfaces, and applied or polished TBC surfaces. While the measured average roughness values of such surfaces may be the same, the effect on external heat transfer may be quite different due to the specific character of the roughness. This task used CRD's Transient Heat Transfer Cascade to test an airfoil coated with TBC that had been polished to various levels, and assessed the effect of TBC-type roughness.

Plans

This task was completed in 1Q97.

Technology Application

The results from this task were analyzed for consistency among the various roughness levels tested. The results were also compared to other, similar tests run in the same facility that used metallic rough surfaces. If the complete set of available data shows a consistent and clear effect of TBC surface roughness on external heat transfer, these data will be used to determine an equivalent TBC roughness for use in the design heat load predictions on the ATS turbine airfoils.

SECTION 2.6 (DE) PRE-COMMERCIAL DEMONSTRATION

This task, which entailed preparation of a commercial proposal and its submission to the host utility, was deleted in 2Q98.