Utility Advanced Turbine Systems (ATS) Technology Readiness Testing

Quarterly Report
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LIST OF FIGURES

ACRONYMS

ACC - active clearance control
ANSYS - finite element software
APS - air plasma spray
ATS - Advanced Turbine System
AWS - aft wheel shaft
CCA - cooled cooling air
CDC - compressor discharge case or casing
CFD - computational fluid dynamics
CMAS - calcium-magnesium-aluminum-silicate
CMM - Coordinate measuring machine
CNC - computer numeric control
CRD - GE Corporate Research and Development
CSMP - Coordination through Short Motion Programming
CTP - critical-to-process
CTQ - critical-to-quality
CVD - chemical vapor deposition
DFSS - design for six sigma
DLN - dry low NOx
DOE - U.S. Department of Energy
DTC - design to cost
EB - electron beam
EDM - electron discharge machine
EDR - electronic data release
EPRI - Electric Power Research Institute
FBD - Free Body Diagrams
FCT - furnace cycle test
FEM - finite element model
FMEA - failure modes effects analysis
FPQ - first piece qualification
FSFL - full speed, full load
FSNL - full speed, no load
GEPS - GE Power Systems
GASP - gravity-assisted shot peening
GEAE - GE Aircraft Engines
GTAW -gas tungsten arc weld
GTCC - gas turbine combined cycle
HCF - high cycle fatigue
HIP - hot isostatically pressed
HRSG - heat recovery steam generator
HVOF - high velocity oxy-fuel
IGCC - integrated gasification combined cycle
IR - infrared
IT - Inverse Time
KCP - key control parameter
KNP - key noise parameter
LCF - low cycle fatigue
LCVT - liquid crystal video thermography
NDE - nondestructive evaluation
NEPA - National Environmental Policy Act
P&ID - process and interface drawing
RAM - reliability, availability, and maintainability
SSPM - steady state performance model
STP - Segment Time Programming
TBC - thermal barrier coating
TBO - time-between-outages
TCP - Tool Center Point
TDM - thermal dynamic model
TMF - thermomechanical fatigue
UAB - Utility Advisory Board
VGV - variable guide vane
VPS - vacuum plasma spray
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 the GE 7H and 9H combined cycle power systems. 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.

This report summarizes work accomplished in 2Q98. The most significant accomplishments are listed below:

9H-Specific

- Initiated 9H full speed, no load (FSNL) test program
- Initiated post-test hardware evaluation
- Initiated analysis of test data

9H/7H-Common Technology

- Continued full-scale H combustor testing at GE Aircraft Engines (GEAE) test stand
- Demonstrated viable high speed, high accuracy thermal barrier coating (TBC) application robot path planning technique
- Held pyrometer design review and received approval to incorporate pyrometers in first H units

7H-specific

- Completed 7H Conceptual Design Review
- Poured 7H compressor discharge case (CDC) and turbine shell castings
- Completed material releases and design review for compressor rotor forgings, compressor blading, and first-, third-, and fourth-stage turbine buckets

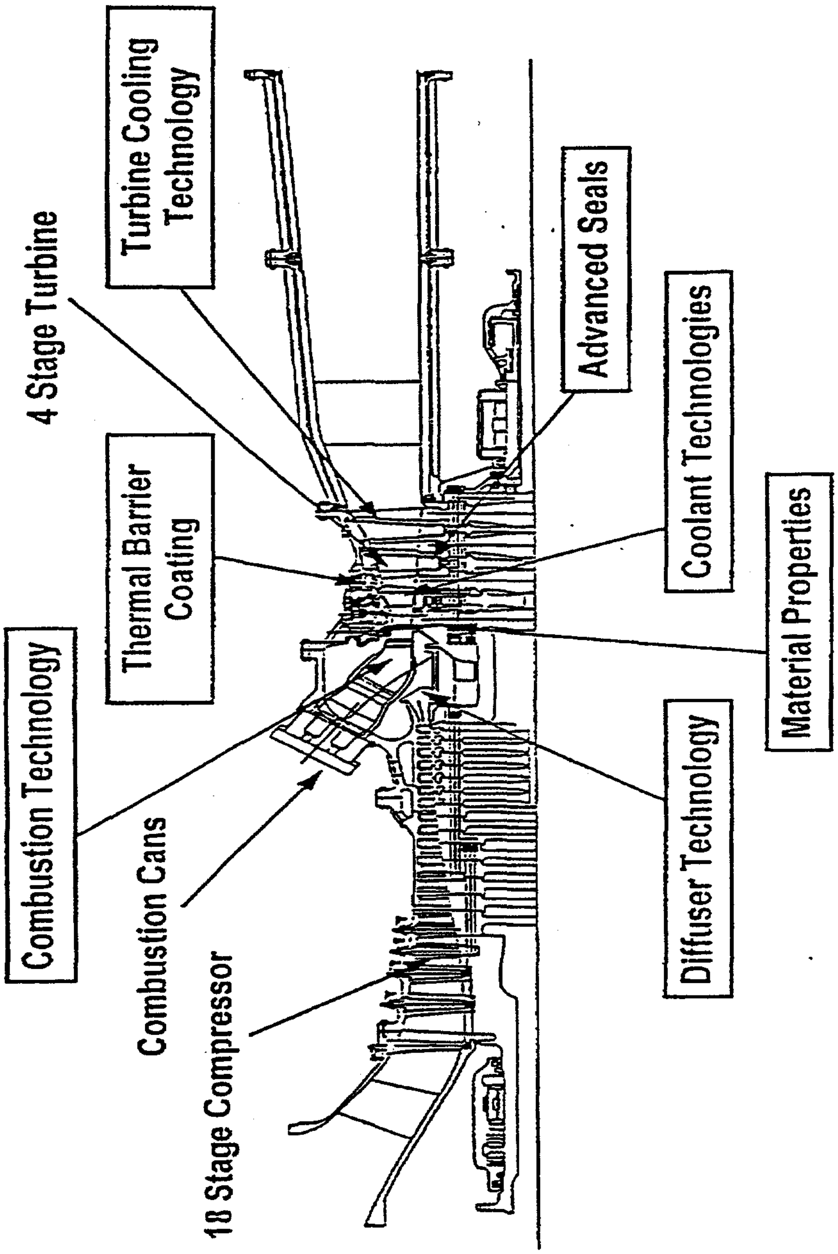

Figure 1-1. Schematic of H machine cross section

SECTION 2 TECHNICAL PROGRESS REPORTS: CURRENT TASKS

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 applying proven GE Power Systems (GEPS) heavy-duty use design practices. The designs will be based on the GE Aircraft Engines (GEAE) CF6-80C2 compressor. Transient and steady-state thermo-mechanical stress analyses will be run to ensure compliance with GEPS 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 7H compressor flowpath was frozen that enabled layouts of the inlet, mid-compressor, and compressor discharge casings, and the tri-passage diffuser to be completed. Electronic data releases (EDRs) fully describing the casing castings as 3D electronic solid models were conveyed to the selected suppliers, who began solidification modeling and pattern work on the respective casings. Conventional casting drawings were initiated.

Internal concept reviews were conducted for each casing, and requested improvements were communicated to the suppliers. Preliminary design analysis was completed for each casing including: blade containment, thermal transients, low cycle fatigue (LCF), creep, applied loads (normal and emergency shipping), internal cooling flows, weld life, normal modes, and bolt/flange sizing.

Significant accomplishments include: enhancing the producibility of the compressor discharge casing (CDC) by eliminating the active clearance control (ACC) in the CDC after a cost/benefit analysis showed that the CDC ACC was not cost effective for the 7H; incorporating numerous producibility enhancements in the CDC diffuser after lessons learned from the 9H were evaluated; and reducing the pressure loss in the CDC strut, which reduced the complexity of the cooled cooling air (CCA) heat exchanger. The 7H compressor discharge case and turbine shell castings were poured.

Plans for Next Quarter

All casting drawings for the 7H inlet and compressor case will be issued. Patterns will be completed at the supplier, and the compressor case and inlet upper half will be poured. Machining drawings will be initiated and analysis to support the drawing release will begin.

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 a combustor based on the commercial DLN2 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.

A full-scale, single-combustor test stand will be designed and fabricated to verify performance of the combustion system. Facility modifications will be made to support the test. These include installation of the test stand, installation of high-temperature stainless steel air piping, an additional air heater, control systems, upgrades to the combustion video system, and tooling.

Progress for this Quarter

The 9H gas turbine was tested at FSNL in the GE Greenville, SC, test facility, and the combustion system performance was as expected.

Additional DLN product configurations were tested at full design conditions at GEAE Stand A2 in Evendale, OH. Premixed load range capability was improved to fully acceptable turndown capability. Combustion dynamic pressures were also fully acceptable with the combustor exit first-stage nozzle blockage bars installed (the closed-closed acoustic boundary condition). Testing with distillate fuel did not eliminate the short liner configuration as the final design, as CO emissions and combustion dynamics were acceptable with water injection.

The 7H transition piece body shape Design of Experiments was completed and a shape was selected based on computational fluid dynamics (CFD), thermal, and stress analyses. This shape was then transmitted electronically to a supplier for fabrication of a cold flow test model.

Plans for Next Quarter

Development will continue on the swozzle-based product combustion system. (A swozzle is a combined swirler/nozzle unit.) The closed-open acoustic boundary condition (exit nozzle bars removed) will be imposed on the combustion system. A primary objective will be to select the length of the combustion liner. Combustion dynamics with bars removed will play a central role in that determination. Combustor exit temperature characteristics on distillate fuel with water injection will also play a significant role.

The 7H transition piece cold flow model will be fabricated and readied for testing.

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, airflow, 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.

Progress for this Quarter

Several turbine wheel Design of Experiments were developed to optimize the turbine wheel shapes. These were also used to optimize the bolt hole and cooling hole sizes and positions.

A conceptual design status review was held on the 7H turbine rotor and steam delivery system. The design was approved to proceed to preliminary design.

Development of parametric subsystem models for the turbine rotor structure preliminary design was started. There will be three subsystem models covering the turbine rotor: the forward end, the aft end, and the midsection. These subsystem models are full parametric, transient thermal mechanical models designed to enable quick, easy changes in geometry.

The IN718 turbine rotor structural forging drawings were released.

Plans for Next Quarter

Dovetail Design of Experiment studies will be completed and the dovetail drawings for long lead tooling will be released. There will be initial runs of the forward end subsystem model and Design of Experiment optimizations will be in process. The aft end subsystem will be modeled in preparation for initial runs.

Spoolie and axial tube conceptual design studies will be completed. The steam system pressure drop Design of Experiments study will be completed, allowing preliminary sizing of the steam system flow areas.

The 1-2 spacer rim configuration will be completed, allowing preliminary configuration of the 1-2 spacer/manifold system to be completed.

Technology Application

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

Section 2.2.2.3.3 (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 CFD, and the results of the analyses will provide the basis for design modifications if necessary.

Progress for this Quarter

The test configuration of the supply manifold was meshed for CFD analysis. This required significant modifications to the original model to simulate the exhaust of air to the environment as well as the actual orifice geometry employed in the test. These changes resulted in a significantly greater number of nodes than originally required to simulate ATS conditions. The CFD code CFX was used to predict the flow distribution in the manifold under test conditions. Despite the increase in the number of nodes, the solution was achieved in less than half the time of the original runs. Test data are currently being processed and comparison of the results will begin soon.

Plans for Next quarter

After the comparison between test data and CFD predictions for the supply manifold is completed, attention will be focused on the return manifold validation effort.

Technology Application

The results of this task define the hydraulic performance and help guide the design of the overall steam distribution circuit and critical individual components it comprises. Performance predictions of various designs are used in trade-off and optimization studies to select the baseline concept of the overall steam distribution strategy and the specific design of the scroll, the supply and return manifolds, and supply and return bore tube and endcaps.

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.

Progress for this Quarter

7H turbine rotor thermal stress analyses were completed, enabling completion of the aft wheel shaft (AWS) conceptual design. The AWS forging drawing was released and the forgings were ordered.

Plans for Next Quarter

This task is complete. Further analyses supporting preliminary and detail design of the AWS will be 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 2.2.2.3.5 (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

Ten buckets with thermal barrier coating (TBC) were installed on an F-class gas turbine. Pyrometer data for the startup of the machine were obtained and are being analyzed.

Pyrometer data from an F-class machine equipped with metal buckets (no TBC) were examined for both long- and short-term stability. The results are considered adequate to fulfill the objectives of this task.

Plans for Next Quarter

Pyrometer data from the test site will be analyzed for stability and trends. A spectrometer system will be installed at the site with metal-only buckets.

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 bench-mark 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

Testing of the supply manifold was completed in 1Q98. The supply manifold test data were reduced in 2Q98. Each supply manifold has one inlet pipe and twelve exit pipes. Six exit pipes go to the first-stage buckets and six go to the second-stage buckets. The objective of the manifold is to distribute the flow uniformly to the first- and second-stage buckets with minimal pressure drop. To determine flow uniformity, mass flow was measured at the inlet to the manifold and at the exit of the exit pipe. To simulate the back pressure created by each bucket, a flow restriction was placed at the end of each pipe. Each flow restriction was calibrated to determine mass flow vs. pressure drop across the restriction.

Data reduction revealed that the total mass flow entering the manifold did not match the cumulative flow exiting the twelve pipes. Because it seemed likely that the mismatch was the result of measurement error, several additional tests were run. The first set of data was discarded since it was not consistent with the additional tests. Within the additional sets of data, repeatability is within ±0.5%, and the variation in mass flow among the pipes is less than that required by the ATS gas turbine.

Initial plans for this task called for flow tests of the ATS gas turbine bore tube. Because of issues related to FSNL scheduling, this testing cannot be done. Under consideration is the testing of a fabricated scale model of the bore tube. Discussions are underway to address this possibility.

An SLA model of the return manifold was fabricated and is being prepared for test. The purpose of this test is similar to that of the supply manifold, that is, to determine the flow uniformity and pressure loss associated with the return manifold.

Plans for Next Quarter

The return manifold will be tested to determine flow uniformity and pressure loss. Plans for a model bore tube test will be completed. A new flow test stand will be built to test spoolies under a range of flow conditions and joint geometries representative of the ATS gas turbine.

Technology Application

The results of this task help 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 will help establish that the performance of these components meets design requirements. Flow distribution, pressure drop, and flow stability will be evaluated.

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

Detailed finite element analysis of the 7H turbine buckets was performed, assessing LCF, HCF, yield, and creep capability to achieve an acceptable design that meets the aerodynamic, life, and performance requirements. Detailed modal analyses were performed to ensure that the buckets have acceptable aeromechanics, and the airfoils were stacked to minimize the moments transmitted to the turbine disks. A heat transfer/cooling analysis was performed on the third-stage bucket to determine the cooling flow needed to achieve the required creep life. Dovetail analyses were performed to ensure that acceptable stresses are maintained. Electronic data releases (EDRs) of the first-stage bucket casting were completed to enable the casting tooling build to begin.

Plans for Next Quarter

Detailed analysis of the 7H buckets will continue to ensure that all design life and performance criteria are achieved to enable EDRs of the second-, third-, and fourth-stage bucket castings. The casting drawings for the buckets will be completed. A detailed 3D finite element tip shroud analysis of the third- and fourth-stage buckets will be completed. Design work on the machining definition of the buckets will be completed. Interface definition with the mating stator components will be completed.

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 2.2.2.4.4 (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 transient liquid crystal techniques in a blade tip cascade.

Progress for this Quarter

The new bucket tip models were assembled and instrumented with thermocouples to investigate thermal losses. The previous tip model used a solid acrylic piece of the appropriate aerodynamic shape. The new tip model incorporates an air gap region between a thin insulator top piece and the bulk acrylic bottom section of the bucket. One model tip is smooth with sharp edges around the perimeter and the other is smooth with radiused edges. New tests were begun to verify the smooth tip heat transfer observed in 1997 testing. Problems were encountered with the adherence of the surface heaters to the remodeled tip material and insulator known as G7. The adhesive tape was replaced by epoxy. In addition to model changes, the inlet ducting of the test rig was modified slightly. The long pre-cascade duct with internal screens was shortened significantly, and the turbulence grid was reinstalled ahead of the airfoil. The previous long ducting was believed to have damped the freestream turbulence level too much. Tests of the sharp-edged tip model show essentially the same heat transfer levels as those of 1997. Tests for heat loss indicate that the tip surface is losing about 4% of the total heater flux as a result of conduction into the model and subsequent convection through side surfaces.

Plans for Next Quarter

The blade tip cascade will be used to obtain a more complete knowledge of the present tip geometries and the associated heat transfer and leakage as well as to test alternate geometries and the effects of deteriorated surface conditions. The inlet turbulence intensity will be measured again for confirmation of previous results. Heat transfer will be determined for at least one alternate rub-strip geometry as well as for one reduced tip clearance gap case. The effect of tip rubs on heat transfer and leakage will also be determined. Testing will be completed.

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

Progress for this Quarter

All slave hardware airfoils for NASA's cascade facility were completed and delivered to NASA. This completes CRD's work scope for this task.

Plans for Next Quarter

NASA's progress will be followed. NASA is currently testing their own blade design in the Transonic Blade Cascade facility. These tests will be followed by heat transfer testing of another GE-designed bucket, which was originally scheduled for 1997. The current progress at NASA would place testing of the ATS bucket in 4Q98.

Technology Application

The results of this task will be 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 2.2.2.4.7 (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

The platform test model design was completed after meetings with the GEPS design team. The model was fabricated but not assembled. The test model is a 3X scale of the first-stage bucket platform underside cavity. The model includes features for coolant delivery, and coolant extraction through both film holes and shank leakage ports. The liquid crystal heat transfer measurement technique requires special features on the model. Surface heaters will be applied to the primary cooled region of the platform. Two trials were performed with an outside vendor to apply roughened surfaces to the heater metal foil or to a thin sheet of copper. Both tests failed to produce a reasonable surface for test purposes. The backup position will now be used to provide surface roughness for the cooled region. Either a grit-laden spray paint will be applied directly to the heater surface, or a copper sheet will be grit blasted, to provide a significantly rougher surface than that of the smooth heater. A small calibration test will be run in an existing impingement coupon rig to quantitatively rank such roughness against the roughness of the first-stage bucket platform, thereby allowing extrapolation of the model data.

Plans for Next Quarter

The platform cooling model will be fully assembled and reviewed for safety. Tests will be performed with smooth surface conditions and the nominal cooling configuration flows and geometry of the first-stage bucket design. The same configuration will then be tested with a rough surface. Results will be reviewed with GEPS engineers to determine the most appropriate variations in cooling to test.

Technology Application

Because of the higher firing temperatures of the ATS turbine and the relatively flat radial temperature profiles experienced by large power turbines, the bucket platforms require more attention to cooling conditions 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 2.2.2.4.8 (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 is to correlate friction factor and heat transfer coefficient data for leading edge passages with 90° turbulators. The accuracy of the correlations developed will determine the need for additional tests with the 7H leading edge turbulated passage first-stage bucket geometry.

Progress for this Quarter

The friction factor and heat transfer coefficient data in the GEAE and CRD database and in the open literature were collected and analyzed. The data were correlated using passage geometric variables and the flow Reynolds numbers. The correlation results show that the leading edge passage Nusselt numbers could be correlated to within ±12% with 95% certainty for a Reynolds number range from 10,000 to 900,000. The friction factor data were correlated to within ±21% with 95% certainty. The results show that the Nusselt number correlation has an acceptable uncertainty, but the friction factors will have to be verified experimentally by running flow tests with a cast leading edge passage and determining their relation to the correlation predictions.

Plans for Next Quarter

Flow tests are planned for the leading edge passage with one cast first-stage bucket.

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 (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

The aerodynamic design of all the 7H turbine stator airfoils was completed. Casting EDRs of the first-, third-, and fourth-stage nozzles were achieved. A detailed 3D finite element analysis of the third-stage nozzle was conducted to determine component stress levels. A thermal/cooling analysis was also conducted on the third-stage nozzle. A detailed finite element analysis of the third-stage shroud was completed to enable the casting definition to be completed. 3D modal analyses of the first- and second-stage shrouds were completed, and detailed cooling and leakage studies were initiated to determine the cooling requirements. Design layout work was completed on the first- and second-stage steam piping system, and an analysis was completed to ensure that acceptable vibration margins were achieved. Detail design of the outer turbine shell enabled the casting definition to be completed. The inner shell machining and fabrication drawings were initiated.

Plans for Next Quarter

Design work will be completed to allow casting EDR of the second-stage nozzle. Further cooling and leakage analysis will be conducted to complete the first- and second-stage shroud configurations, and the casting definition of these components will be released. Detailed machining definition will be completed on the third- and fourth-stage nozzles and shrouds, and 3D thermal and mechanical analyses will be conducted to determine component lives and establish cooling requirements. Component interfaces will be established and a detailed turbine flow/leakage analysis will be conducted.

Technology Application

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

Exhaust Frame and Diffuser

The 7H exhaust aerodynamic flowpath was frozen. The master layout defining the structural frame and the diffuser liner was completed and casting drawings (gib key and aft support trunnion) required for the fabrication were issued. A supplier was down-selected based on previous layout releases. Ongoing workouts with the supplier identified a number of cost reduction concepts (identified from 9H lessons learned) that are being evaluated for the final drawing layout release.

Preliminary analysis, including Free Body Diagrams (FBDs), weld sizing, and casing thickness were completed. Casing thickness was determined from the blade-out, shipping, and normal operation loads analysis. Diffuser normal modes finite element model (FEM) analysis was completed, and results show the predicted response to be very similar to the 9H.

7H Steam Gland

The 7H steam gland concept was frozen and solid modeling of that concept was completed. Support arms and gibs as well as the steam scroll were sized. The solid model definition was conveyed to the supplier and solidification modeling and pattern work were initiated.

2D mechanical static analysis and preliminary 2D thermal transient analysis were completed. Bolts and flanges were sized using the FLG2D program.

Plans for Next Quarter

Exhaust frame fabrication drawings will be issued and machining layout will be initiated. Flange and bolt sizing and cooling airflow analysis will be completed.

The steam gland casting drawing will be completed and issued. Detailed 2D thermal/mechanical transient analysis and clearance analysis will be completed.

Technology Application

This analysis and design effort establishes the basis for the 7H and 9H 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 on completion of the 9H FSNL test and 7H conceptual design.

The initial 9H FSNL test was completed on time and met all test objectives. The gas turbine operated flawlessly, and the test stand operated successfully with minor problems as the system checkouts were completed. An effort was made to include potential customers in the test environment and feedback was extremely positive. The gas turbine is currently being disassembled and evaluated as part of the test plan.

The 7H has completed a leaders' review of the Conceptual Design tollgate in preparation for a formal business review and go-ahead. Cost, schedule, risk, and performance metrics were reviewed and updated to support the requirements of this tollgate. All material was released and suppliers were selected, initiating the manufacturing process.

Supporting technology development that benefits both the 9H and 7H turbines is ongoing.

7H system level studies continued to be performed to optimize cost, performance, weight, size, maintainability, reliability, and manufacturability. Optimization was limited only by schedule as decisions were made to support the 7H first unit assembly. Performance, cost, weight, and other system level and integration issues are being monitored and tracked. The systems review team, which includes engineering, manufacturing, sourcing, and maintainability personnel, continue to meet to review the merit of system issues and determine whether incorporation of ideas meets system goals.

A meeting of the Utility Advisory Board (UAB) was held to update the U.S. utilities on the progress of the GE H gas turbine. The cross-section drawings were updated for the 7H, reflecting conceptual design configuration and interface decisions.

The maintainability, reliability, and serviceability team continues to work to ensure that all of the lessons learned for field operation are being incorporated into the 9H/7H design. Reliability, availability, and maintainability (RAM) and failure modes effects analysis (FMEA) studies were completed, and goals were established for the H machines consistent with the Product Specifications.

Plans for Next Quarter

The 7H design to cost (DTC) and performance models will be updated to include the latest configurations. Systems studies and decisions will continue, supporting ongoing development. Customer support will continue, ensuring that the final H configuration meets the customer needs.

9H gas turbine evaluation will be completed, and the 9H gas turbine will be rebuilt to support extended FSNL testing.

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 2.2.2.7.1 (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.

Progress for this Quarter

The transient gas turbine cycle model (without the heat soak, clearance, and stress model) is being used for various system and control studies within the overall combined cycle plant transient model.

The heat soak model was completed and is currently undergoing checkout. All data (heat transfer and weight breakdown) available from the mechanical designers were used in the model. Model data required but not available from the designers were estimated.

Additional features, including the effect of pumping and pressure losses in the circuit, were added to model the cooling steam flow circuit. This was also done for air in the steam cooling passages. The heat transfer and pressure loss factors representing air in the steam cooling passages were scaled appropriately from the steam values.

Plans for Next Quarter

Comparison of the heat soak model to more detailed analyses will be completed, and the model will be integrated into the ATS gas turbine transient model. Work on the stress model and clearance will be initiated and completed.

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 ±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 2.2.2.8 (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

All on-base piping, turbine base, and electrical documentation required for the first FSNL test was completed, fit-up, and installed on the FSNL test unit. Actual installation at the test stand went smoothly as a result of the design process and fit-up activities included in the overall plan implemented to fulfill the task objectives. All hardware ran successfully during FSNL testing.

The data collected during the FSNL test for this hardware will be fed back into the on-base designs. These data will be used to improve those first FSNL designs, as well as to complete the balance of non-FSNL tested systems.

Plans for Next Quarter

All data from the first FSNL testing will be reviewed, and the results will be applied toward all affected hardware required for design completion and the second FSNL testing.

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 and 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 9H gas turbine unit was installed in the new Greenville, SC, factory test stand in April 1998. The unit was installed with all of the gas turbine skids, control system, and starting means, and the protective and compressor-related instrumentation was hooked up for data test monitoring and data collection.

Initial FSNL test runs were complete by early June1998.

The measured compressor airflow, pressure ratio, and efficiency were as predicted. The unit vibrations, bearing operation, and wheel space temperatures were also as predicted.

A post-test data design review was held on June 26, 1998.

Plans for Next Quarter

The gas turbine unit will be taken back to the factory for disassembly and hardware inspection.

Technology Application

These are test plans to establish the instrumentation requirements for 7H and 9H FSNL and full speed, full load (FSFL) tests.

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 2.2.3.1 (GTETNC) S1N DESIGN

Both tasks reported in Section 2.2.3.1 were completed in 1996.

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.

Progress for this Quarter

The steam supply manifolds are used to distribute steam to the buckets. Due to the unique geometry of this component, pressure losses need to be measured to determine the effects on the supply of cooling steam to the buckets. A flow test rig was used to test and characterize the pressure losses in the manifolds and will be used to help validate the analytical models that will also model the rotational effects on the steam flows. The test data from the supply manifold test raised questions regarding the calibration of the metering orifices used. When portions of the test were rerun, results showed acceptable agreement between test and analysis.

Plans for Next Quarter

The return steam manifold flow test rig will be assembled and the flow tests will be started. A CFD analysis will be conducted on the test return manifold and compared with the test data.

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) Rotor-Bucket Steam Transfer Spoolie

Objective

Rotating air rig tests will be performed to validate the steam transfer spoolie design concept. (Spoolies are the hollow, spool-shaped ducts that bridge the gap between the steam delivery channels in the turbine rotor and cooling channels in the buckets.) A stationary steam test rig will be used for evaluation of durability and alignment effects on leakage.

Progress for this Quarter

Coating qualification for spoolies was completed. Durability of coating tests are partially completed on the small size spoolies. These tests successfully demonstrated the spoolie coating wear rate and coating durability in a steam environment. Test samples were acquired for the optimum coating system.

Plans for Next Quarter

Further tests are planned for the spoolie steam wear/leakage rig, investigating alternate coating manufacturing parameters in the pursuit of optimum wear and leakage. The alternating side load rig testing will help verify LCF predictions.

Technology Application

These tests will validate the rotor bucket steam transfer spoolie design.

Section 2.2.3.4 (GTETRH) ROTATIONAL HEAT TRANSFER

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 is to measure the heat transfer coefficients in a constant-area duct that captures all of these features. Tests will be performed in the full-scale rotational test rig.

Progress for this Quarter

Construction continued on the new test payload, which is close to completion.

Plans for Next Quarter

In 3Q98, the payload will be installed in the test rig, and all data will be acquired.

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 (GTETIH) SURFACE ENHANCED INTERNAL HEAT TRANSFER

Section 2.2.3.5.2 (GTETIH) S2B Trailing Edge Heat Transfer Tests

Objective

The objective of this task 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.

Progress for this Quarter

Preliminary design reviews were held with GEPS design engineers to gain an understanding of the current geometry of the second-stage bucket trailing edge internal tip region and to determine key features for model tests. The 2X acrylic test model was designed and fabricated. The surface heaters needed for this task were made available. Small modifications were made to the actual cooling passage geometry to accommodate machining limitations as well as potential surface heating difficulties. These changes are manifested in the test section inlet geometry, which incorporates a constant cross section unheated length for development of the hydrodynamic conditions, followed by a heated section to develop the thermal conditions. The inlet approximates the passage geometry. The thickness of the interrupted internal radial ribs, turning vane, and passage rib were decreased to avoid overheating the surfaces underneath. These ribs will still perform the correct flow direction function intended. The model is being assembled.

Plans for Next Quarter

First, a pre-test review will be held with GEPS to confirm the desired test conditions and to address differences between the model and the geometry of the second-stage bucket. The model will then be reviewed for safety considerations, and testing will be initiated. Results will be compared with liquid crystal results from a previous test model that focused on the passage mid-span region. Testing will also be performed to optimize the tip turn region.

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.

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. The flow and heat transfer inputs for the design are complex and need verification testing.

Specifically, the objective of the 1998 task is two-fold: to measure friction factors and heat transfer coefficient for the low-aspect-ratio/high-blockage trailing edge turbulated holes, and to support and verify a trailing edge region cooling design.

Progress for this Quarter

Trailing edge cavity heat transfer tests were conducted in an acrylic test section modified to form a 0.4-inch × 1-inch flow passage. The first series of tests was conducted with a smooth tube. The heat transfer coefficients measured with the smooth tube are within ±15% of the expected values. The second series of tests was conducted with turbulators. Additional tests were also conducted with medium height turbulators having square or rounded edges. The testing covered Reynolds numbers ranging from 25,000 to 100,000. The measured friction factor and the heat transfer coefficient enhancements were compared with the CRD database predictions. The friction factors at the low blockage ratios are close to the values in the database; the difference between the measured friction factors and the values in the database increases with the turbulator height. The heat transfer coefficient enhancements varied with the turbulator height and flow Reynolds number.

Plans for Next Quarter

The pin-fin-cooled region of the trailing edge will be investigated. First a model that can predict frictional losses and heat transfer coefficients for pin fins will be verified against data available in the open literature. The model will then be used to optimize the present pin fin configuration and increase the heat transfer coefficients. Based on these results, tests will be conducted to verify the predictions.

Technology Application

The friction 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.

Section 2.2.3.5.11 (GTETIH) Production Airfoil Flow Checks

Objective

The cooling flow circuits of the first- and second-stage nozzles and buckets of the ATS gas turbine have complicated flow configurations. 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 and bucket components. 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

A cast first-stage bucket was received for flow testing. The static pressure hole locations were positioned and marked for electron discharge machine (EDM) drilling. Several additional machining steps were initiated at the machine shop in order to prepare the cast part for flow testing.

Flow tests were initiated for cavity 7 (the convectively cooled cavity) of the first-stage nozzle. Borescope inspections of the turbulators in cavity 7 were performed. Three static pressure taps were drilled at the inlet and exit sections of cavity 7 for the two cast nozzles. Flow tests were conducted with one of the nozzles at Reynolds numbers from 30,000 to 50,000 with atmospheric discharge. The measured flowrates for the inlet-to-discharge pressure differences agree with the calibrated design flow model. Tests will be repeated with the second nozzle to check the variations from part to part and at high pressure discharge ambient to reach Reynolds numbers of approximately 300,000.

Plans for Next Quarter

The necessary flow tests and static pressure distribution measurements for the first-stage bucket and first- and second-stage nozzles and shroud cooling circuits will be performed.

Technology Application

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

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 forms of internal fillet regions in the first-stage nozzle design: (1) the airfoil insert impingement into the spanwise cavity rib fillets and (2) 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

CRD and the GEPS design team initiated this task by identifying the representative airfoil and endwall locations to be examined. Preliminary design reviews confirmed the key features and established the arrangement of the test models to be used. The endwall edge region fillets for both inner and outer endwalls will be tested first. The airfoil-internal rib fillet tests will follow. The inner and outer endwall geometries in these edge fillet regions are different in ways that may affect the resulting impingement heat transfer distributions. Two acrylic test models were designed, each a 10X version of a representative fillet region. The models retain all the key surface features that may affect flow distribution and heat transfer. Quotes for fabrication of the models were requested. Surface heaters were ordered. Fabrication of the coolant impingement plenum was completed.

Plans for Next Quarter

A review of the model design and test points will be held with GEPS. The models will be completed and the heaters delivered. One model will be assembled and reviewed for safety. The first-stage nozzle design will be tested at nominal conditions for each endwall fillet model.

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 liquid crystal test models will provide detailed heat transfer coefficient distributions for the specific geometries of the 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 2.3.7 (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.

Progress for this Quarter

No additional testing was performed during 2Q98.

Plans for Next Quarter

The test plan under this task has been put on hold pending a decision as to whether or not to proceed with this task.

Technology Application

The results of the tests conducted as part of this task will be 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 Particulate Deposition Rig Testing

Objective

The objective of this task is 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 is to be translated into a steam purity specification and full-filter specification for the ATS gas turbine. The approach employed is 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 will be used to verify the predicted time-between-outages (TBO) results from ATS Phase 2 studies.

Progress for this Quarter

No additional testing or analysis was done in 2Q98. However, the steam purity effort reached a milestone with the placement of a commercial order for a filter system for the initial 9H gas turbine. The filter specifications were based on the technical results of the deposition experiments at the power plant as well as on practical experience with equipment protection, assembly and disassembly, and filter cleaning.

Plans for Next Quarter

A formal review will be held to discuss results from the static specimen particulate deposition tests completed in 1997. The apparatus will be removed from the power plant site and stored at GE's Main Plant in Schenectady for up to two years in the event that further testing, perhaps on a slip stream at the prototype plant, is deemed necessary.

Technology Application

The proper particulate filtering of steam used for bucket and nozzle cooling is critical to the reliable long-term operation of the ATS gas turbine. Data from tests under this steam particulate deposition task made it possible to establish the necessary steam filter specifications. Moreover, experience with steam system cleanliness developed on the program has been helpful to prototype first start-up procedure development.

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, LCF, 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

Two additional sets of creep data in steam were collected from forged material. One test was conducted on IN718 "Ingot 3" material and one on "Ingot 4" material. These results were compared to air and steam data, which were collected earlier, and distributed to Design Engineering. Retorts and fixturing to perform LCF tests in steam were completed. Fixtures to permit crack growth rate testing in steam are almost complete.

A detailed test plan was developed to study the influence of grain size on tensile, LCF, and crack growth behavior in cast IN718 that would be used in the steam delivery system. The objective of the study is to rationalize the influence of steam and grain size on LCF life and crack growth behavior. Test data will be used to develop lifing criteria for various components. A Design of Experiments approach was used for LCF testing. Two grain size ranges were selected for casting trials. The casting vendor was identified for the manufacture of test slabs. LCF testing and data analysis of cast+HIP IN718 material are in progress. Four steam LCF specimens and four air LCF specimens were machined and submitted to the testing house.

LCF specimens were machined from additional first-stage airfoil material and second-stage bucket material. Twelve LCF specimens were machined from additional first-stage airfoil material and 26 specimens from the second-stage bucket material. All samples were delivered to the testing house. Material representative of an alternative bucket tip cap material was obtained. Machining of LCF specimens was initiated.

Plans for Next Quarter

Tensile, LCF, and compact tension specimens will be machined from cast IN718 material. Tensile tests will be conducted at three different temperatures. LCF tests will be initiated on cast IN718 material at one temperature and several strain ranges. LCF specimens will be machined from the alternative bucket tip cap material. Additional samples of the second-stage nozzle material will be procured, and crack growth specimens will be machined from second-stage nozzles to confirm earlier slab data.

Technology Application

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

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.

Progress for this Quarter

Revision of the General Requirements process specification used to define the acceptance criteria for the 7H outer turbine shell and compressor discharge case was completed. Associated drawings were reviewed and approved. Design concept reviews were held for 7H compressor structural components which included the inlet case and the compressor discharge case. First piece qualification (FPQ) requirements for the 7H compressor structural components were reviewed to implement lessons learned from earlier work on the 9H.

Plans for Next Quarter

Additional supplier meetings will be held as warranted. Evaluation of alternative methods of manufacture will continue.

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.

Progress for this Quarter

The second set of IN718 forgings was evaluated against metallurgical and ultrasonic requirements. Indications of interest were evaluated and each of the forgings was dispositioned for use. The forging process was optimized through sub-scale Design of Experiment trials. The ultrasonic test results have been used as a gauge to monitor progress. A study was initiated at the melter to enhance understanding of some of the process variables and their effect on ultrasonic test results. Small ingots of the diameter of interest will be melted with various process variables and evaluated for defects.

A preliminary study to determine the optimum transducer frequency for detection of ultrasonic indications in IN718 forgings was completed. This information will be used to design an improved ultrasonic inspection system for these components.

Additional smooth bar LCF test results collected in 2Q98 were combined with existing forged IN718 LCF data to generate new and revised Handbook LCF curves. The results were communicated to Design Engineering. Additional hold time LCF tests in air of "Ingot 4" material continued. To date, tests have exceeded 3,000 cycles. Twelve of fifteen planned creep tests of "Ingot 3" IN718 forged material were completed. The longest tests have approximately 19,000 hours of test time. Six of the eleven planned creep tests of "Ingot 4" material were completed. The longest test has accumulated approximately 10,000 hours of test time. New and revised Handbook curves were published for creep and rupture characteristics of forged IN718. The results were communicated to Design Engineering. Static and dynamic crack growth rate testing of forged IN718 was initiated with "Ingot 4" material. Additional HCF tests of forged "Ingot 4" material were completed. The results were communicated to Design Engineering.

Plans for Next Quarter

Design of Experiments melt variable studies will continue. Evaluation of correlation of ultrasound results to features in the forgings will continue. Development of an enhanced ultrasonic inspection system will proceed. Creep rupture tests and hold time LCF tests will continue. Handbook curves will be updated as additional test data are analyzed.

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.

Progress for this Quarter

Welding trials continued in support of rotor steam delivery manifold manufacture. Several manual gas tungsten arc weld (GTAW) welded coupons were made and examined for soundness with x-ray and metallography. Several return and supply manifolds for rig test were welded successfully. A viable weld sequence was determined that would minimize distortion. Development of a flux GTAW process for the manufacture of manifolds continued. Welders were trained with this revised process and it was used successfully to manufacture several return manifolds.

Casting producibility trials targeted at the 7H manifold were initiated at a supplier. Three castings will be made. Concurrently, a development program was initiated to produce slabs of IN718 to permit evaluation of the resulting mechanical properties as a function of the casting process parameters. A part specification for the manufacture of elbows was revised.

Development of an electron beam (EB) weld procedure at the bore tube supplier was completed successfully. Support of suppliers leading to qualification continued for the radial tubes and axial tubes. The part specification for the spoolies was revised.

Fourteen sliding wear tests were completed on the selected wear coating prepared with various processing conditions. A half-fractional designed experiment was set up to determine whether oxide level, heat treatment, deposition gun, or testing temperature affected the performance of the coating. Coefficient of friction data indicated that some improvements can be made by optimizing processing. Confirmation runs are scheduled. Four surface treatment options for the rotor steam delivery system material were selected to minimize coating spallation. Samples were fabricated and will be tested in 3Q98. Fabrication of specimens for the determination of elastic-plastic and thermal properties of the coating continues.

Tensile testing on an alternative rotor steam delivery material was completed at two temperatures of interest. Tensile testing of GTAW welded and unwelded alternative material was also completed and a report issued to Design Engineering. Manual GTAW weld coupons of IN718 material were obtained, machined, and heat treated prior to mechanical testing.

Plans for Next Quarter

Supplier qualification of various cast components and weld procedure development will continue. Work is planned to continue wear testing and confirmation of the coatings produced by various processes and also to test four alternatives to the current coating. Samples for determination of the coefficient of thermal expansion will be machined and measurements made. Tensile, LCF, stress rupture, and bend test specimens will be machined from IN718 manual GTAW welds. Tensile tests will be conducted at four temperatures. One stress rupture test will be initiated.

Technology Application

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

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 employing 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 were initiated on milled specimens of the first-stage airfoil material to determine the effects of milling-induced recrystallization on LCF. Three groups of LCF specimens with three different surface finishes were put into test. The test temperatures include both a maximum operating temperature expected of the first-stage nozzle in the ATS turbine and a relatively low temperature. Four strain levels are being tested at each temperature.

Alternative bucket tip cap test material was obtained from a supplier. Various types of test specimens are currently being machined from this material, including specimens for tensile, creep, LCF, and HCF tests. These specimens will then be tested to generate design curves.

Specimens of first-stage bucket material castings with intentionally placed internal defects were tested for HCF at one selected temperature.

Additional design curves were issued for the third-stage nozzle material, the first-stage airfoil material, and the second-stage bucket material. These included LCF curves at five different material/temperature combinations and HCF Goodman diagrams for nine different material/temperature combinations.

Investigation of new aft-stage bucket alloys for the 7H was initiated. Aft-stage buckets in existing production configurations using the proposed alloys were cast by a supplier. The buckets were subjected to a standard post-cast heat treatment cycle. Tensile specimens were then machined from these buckets and tested at eight temperatures. Creep test specimens were machined from the same buckets and tested at four different temperatures and stress levels.

Plans for Next Quarter

LCF testing of milled first-stage airfoil material will be completed. Additional HCF specimens will be machined from first-stage airfoil material and second-stage bucket material. Simulated defect-containing LCF specimens will be machined from first-stage airfoil and second-stage bucket material. Evaluation of processing and mechanical properties of the proposed 7H aft-stage bucket materials will continue.

Technology Application

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

Section 2.2.4.11 (GTMTCB) Combustion Materials and Processes

Objective

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

Progress for this Quarter

Baseline creep testing of the sheet material was initiated. Most of the LCF tests were completed. Welded sheets to support LCF, creep, and tensile testing were sent out for specimen machining.

Plans for Next Quarter

Creep testing will continue. Welded specimens will be inspected with fluorescent penetrant to determine whether they are viable specimens for mechanical testing. Creep, tensile, and LCF testing on welded bars will be initiated. Analysis of baseline test data collected earlier will begin.

Technology Application

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

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

Refinement of braze and weld repair processes for first- and second-stage airfoil materials continued. Repair development was implemented for the second set of hardware. Additional laboratory-produced brazes and welds were evaluated and screened based upon limited mechanical property tests.

Plans for Next Quarter

Studies will continue to evaluate and enhance repair methods for hot gas path materials with selection of process and subsequent optimization of parameters.

Technology Application

The ability to repair airfoils will result in more cost-effective flowpath components.

Section 2.2.5 (GTTT) THERMAL BARRIER COATING TECHNOLOGY

Section 2.2.5.1 (GTTTSD) Coating System Development

Objective

Plasma spray thermal barrier coating (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 will be developed. Surface finishing techniques will be developed.

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 on 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 that most strongly influence process variability and TBC quality.

The TBC nondestructive 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 Airfoils

The three FANUC Robotics M710i/RJ2 systems (two development systems located in Schenectady, NY; one production system located in Greenville, SC) were configured to ensure matched performance. The RJ2 Robot Controllers were upgraded to accept 4 times larger robot programs, translate programs 8 times faster, and transfer files 20 times faster. A remote user interface is being developed by CRD.

A Visible Laser Measurement System was developed for use by the robot operator during motion verification. Measurement accuracy was improved by 50 times by using a higher resolution laser, improving signal-to-noise ratio, and installing a simpler user interface. A new laser target was developed for measuring surface velocities in fillets, with testing planned for 3Q98.

Both nozzles and buckets require simultaneous movement of the spray tool and part to properly access all part surfaces and satisfy the process requirements for surface velocity, standoff distance, and spray angle. Four methods for robotic motion control and programming were developed and tested. Two approaches were forms of Tool Center Point (TCP) motion control that require stationary targets in order to define motion along the 3D part surface. These approaches were inadequate because of the geometric complexity of the ATS hardware. The other two methods were forms of inverse time motion programming, which allow simultaneous movement of the spray tool and part. The first is a FANUC Robotics product called Segment Time Programming (STP), which utilizes the built-in path planning capabilities of the RJ2 controller. The second is a custom form of Inverse Time (IT) developed for GE by FANUC Robotics. Both STP and IT demonstrated motion control performance within the requirements for the ATS program. Initial motion programming approaches for nozzles and buckets were selected. Designed experiments are being used to optimize motion programming for various parts.

Two off-line robotic motion simulation systems were developed and tested. The first is a Tecnomatix product called ROBCAD, which supports full 3D modeling of robotics motion with capabilities for detecting motion limits (position and velocity) and collisions. Planned ROBCAD enhancements will further improve functionality and reduce the amount of time required to perform collision detection. The second simulation tool is a CRD product called

Coordination through Short Motion Programming (CSMP). CSMP takes into account the robotic system capabilities for motion position, velocity, and acceleration based on equipment characterization studies performed at CRD. Version 1.0 of the CSMP-ROBCAD Advisor software was delivered to GEPS. This is an off-line tool for checking robot motions programmed using ROBCAD/STP.

An off-line simulation tool to predict TBC thickness on ATS airfoils will be developed. This will be accomplished by modifying a tool used to predict the thickness of metallic overlay coatings applied by vacuum plasma spray (VPS; two degrees of freedom). The new tool is needed to reduce the cycle for developing robot motions for TBC (seven degrees of freedom), improve powder efficiency, and achieve more uniform TBC thickness distributions.

Nozzle Coatings

The ATS nozzle replica was used for two sets of designed experiments, beginning with constant velocity tests and leading to a series of variable velocity tests. Motions were developed using ROBCAD/STP programming. The constant velocity "patch" motion performance was within specifications and very repeatable. Variable velocity "patch" and "continuous" motion trials are planned.

Production ATS first- and second-stage nozzles were received for coating trials. Qualification of production coating processes is scheduled for completion early in 1999.

Bucket Coatings

The ATS bucket replica was used for constant and variable velocity tests. The constant velocity "patch" motion trials were slightly outside specifications but very repeatable. These trials were conducted at both GEPS and CRD, and motion equivalency was excellent. A series of variable velocity trials was conducted at CRD using both ROBCAD- and CSMP-generated motions. Although the differences in coating quality were minor, it was demonstrated that the CSMP-generated motions were superior in regions with short velocity transition zones.

Production ATS first-and second-stage buckets were received for coating trials. Qualification of production coating processes is scheduled for completion in 4Q98.

Shroud Coatings

A second iteration of spray trials was completed on shroud replicas and metallographic evaluation is underway. Production spray fixtures were procured for both first- and second-stage shrouds. Qualification of production coating processes is scheduled for completion in 3Q98.

Transition Piece Coatings

Note: *This development is being conducted under an internal (non-ATS) program. Reporting will continue to provide continuity between the ATS and non-ATS work scopes.*

Mechanical testing was completed for the two coating processes selected as cost-saving alternatives to the advanced coating process. Coating properties were measured as functions of furnace exposure time/cycles to predict coating life under service conditions. The coatings manufactured by the alternative processes were sufficient to meet ATS requirements, but with a significantly reduced margin of safety compared to coatings manufactured by the advanced process. The relative merits and drawbacks associated with each of the three coating processes were considered, and the advanced process was selected for use on the first set of production parts. Qualification of this process for production is scheduled for completion in 3Q98.

Bond Coat Processes

(A) Thermal spray bond coats

Note: *This development is being conducted under an internal (non-ATS) program. Reporting will continue to provide continuity between the ATS and non-ATS work scopes.*

Testing and evaluation of protective thermally sprayed bond coats on substrate materials to be used for first- and second-stage airfoils, shrouds, and transition pieces continued with additional furnace cycling and oxidation rig hours accumulated. A selection of bond coats for the first ATS hardware was completed, and specifications were written for the materials and techniques chosen. The focus in 1998 is the development of a new bond coat chemistry that is expected to meet all ATS requirements.

(B) Brazed bond coats

Braze coating processes may be needed to meet ATS requirements on certain components where spray gun access is restricted. These components include the transition piece and second-stage nozzle weld joint, which can be sprayed using air plasma spray (APS) guns only. The as-sprayed bond coats are not sufficiently protective to certain substrate alloys, particularly GTD222. Two types of braze-APS coatings are being evaluated: Type 1 coatings are brazed oxidation barriers applied to the substrate followed by APS bond coat and TBC; Type 2 coatings are mixtures of braze and bond coat alloy co-sprayed by APS followed by TBC.

Coatings for CMAS Mitigation

Note: *This development is being conducted under an internal (non-ATS) program. Reporting will continue to provide continuity between the ATS and non-ATS work scopes.*

Testing of coatings prepared by two alternate chemical vapor deposition (CVD) processes was performed, with one process selected for continuing development. New samples with alternate chemistries are being prepared.

TBC Manufacturing Technologies

(A) Surface finishing methods

Controlled TBC surface finishing methods are being developed to ensure both acceptable surface finish and uniform material removal over all regions of the airfoils, fillets, sidewalls (nozzles), and platforms (buckets). Conventional finishing techniques, such as tumbling and grit blasting, were 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. Continued development is focusing on computer numeric control (CNC) machining operations such as grinding, belting, or milling.

A coated ATS second-stage nozzle was provided to the CNC machining vendor, and development of fixtures, grinding wheels, and machining motions is underway. A second nozzle will be coated to allow faster turnaround of finishing trial iterations. Machining trials will begin in 3Q98.

Cost and process times for the CNC machining are significantly higher than for current production finishing, however, so alternative processes will continue to be explored with appropriate cost/benefit and risk analyses performed. Gravity-assisted shot peening (GASP) followed by hand polishing is used for production finishing of TBC-coated buckets for non-ATS gas turbines, and may be acceptable for ATS buckets. Extension of this process to ATS nozzles will require robot-controlled shot peening. Trials are being conducted with various media types and sizes to improve this technique. A second alternative finishing technique that utilizes part-specific soft tooling and conformable abrasive media demonstrated promising results on flat samples and is being further evaluated on buckets.

(B) Second-stage nozzle doublet joint

Several processes for applying bond coat and top coat to the welded joint of the second-stage nozzle doublets have been evaluated. These nozzles are cast as singlets and welded into doublets following application of TBC to the nozzle airfoil and sidewall surfaces. The prime focus is a high velocity oxy-fuel (HVOF) bond coat with an APS top coat. Spray trials were conducted using coated plates having an uncoated trough to simulate the weld joint area. Masking techniques to protect the pre-existing TBC and preserve the microstructure of the blended area were identified.

<u>TBC Process and Diagnostics</u>

(A) Alternative plasma guns

Plasma guns that operate at longer standoff distances and higher powder injection rates are desired for manufacturing. Experiments were performed to evaluate coatings sprayed using three alternative guns. At least one gun has the capability of achieving similar or better TBC properties than the current gun at much longer standoff distances and over 4 times higher powder injection rates. Additional designed experiments were performed which increased the deposit efficiency by over 2 times. The experiments suggest that different anodes may be required to deposit bond coat and top coat, however, which is undesirable for manufacturing.

A second alternative gun showed no advantage over the current gun when operated within the manufacturer's recommended power range. Additional designed experiments were performed at the highest power level this gun can tolerate, with very encouraging results. The third alternative gun has experienced significant reliability problems and will be evaluated as a longer-term effort.

(B) Process variables that control as-sprayed TBC roughness

Evaluations of process variables that control as-sprayed TBC roughness are being conducted to minimize the need for post-spray TBC surface finishing and/or to improve the effectiveness of low cost TBC finishing processes. The baseline finishing process is GASP followed by hand polishing. Samples were machined from plates having varying degrees of TBC roughness. The samples were welded to a production bucket and put through a standard GASP cycle to assess the effect of as-sprayed roughness on roughness following GASP. A strong relationship between as-sprayed and as-GASPed roughness was observed.

Regression models to predict as-sprayed surface roughness were developed for the current spray gun and one alternative gun. Samples sprayed with the current gun were GASP finished, but the model predicted that this gun must be operated significantly outside its optimal process window in order to achieve acceptable surface roughness without post-GASP finishing. The model for the alternative gun predicted that acceptable surface roughness without post-GASP finishing can be achieved with small changes to the gun operating parameters, which are within its optimal process window. A designed experiment will be performed in 3Q98 to refine and validate the model predictions for the alternative gun.

(C) Transfer of technology for TBC process sensors

TBC process sensors evaluated by CRD in earlier ATS years and parallel programs were selected for transition to GEPS.

The infrared optical pyrometer data acquisition system was successfully tested during coating of an ATS second-stage nozzle. Specifications for the system were established.

Nondestructive 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) in Schenectady and Greenville are used as the scanning devices. Two flexible eddy current probes of different configurations will be used initially to inspect ATS nozzles and buckets fully.

The automated systems were installed in Schenectady and Greenville. A third system was installed by the CNC machining vendor to support development of nozzle surface finishing. Fixtures for all ATS buckets and nozzles were delivered. CMM motion programming and control are performed using either the DEA Master "P" language or a Tecnomatix software product called VALISYS. This software was installed and successfully tested with the automated inspection system in Schenectady and is being installed in Greenville. CMM programming in both VALISYS and DEA Master "P" is underway for all parts. DEA Master "P" programs for the second-stage nozzle and both the first- and second-stage buckets were successfully tested.

An upgraded manual TBC thickness measurement system using a Nortec 24 eddy current instrument and a flexible eddy current probe was installed in Greenville. A new 6-axis CMM, which will offer three more degrees of freedom than the conventional 3-axis CMMs now installed, was purchased for installation in Schenectady later this year. The final machine design was reviewed and approved, with installation planned for 3Q98.

Nondestructive TBC Microstructure Evaluation

Laser Ultrasound is being developed for nondestructive evaluation of TBC microstructures. The laser ultrasonic approach uses a Nd:YAG laser to produce a shaped source beam onto the target coated substrate, generating an ultrasonic Lamb wave that propagates in the 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.

The new laser ultrasound interferometer has been completed and validation of its performance against previously characterized samples is underway. The Quality Function Deployment conducted in 1Q98 showed that a lower cost instrument with reduced standoff is also desirable. Experiments conducted on a Sagnac interferometer showed that this instrument may meet the defined requirements.

A review of the CNRC/IMI joint activity on measurement of elastic moduli was held in May. A coated ATS cascade nozzle was provided by GEPS for correlating laser ultrasound signatures with coating microstructure and mechanical properties.

Plans for Next Quarter

Robot Motion Control and Part Coating Trials

ROBCAD/STP motion development based on constant and variable velocity trials on ATS hardware and replica shapes will be continued.

The best approach to embedding CSMP capabilities into the ROBCAD software will be determined.

Coating processes on production ATS components will be qualified.

TBC Manufacturing Technologies

CNC grinding trials using an ATS second-stage nozzle will be conducted. Investigation of robot-controlled shot peening for ATS nozzles will continue.

Process development for coating of the second-stage nozzle weld joint will continue.

TBC Process and Diagnostics

All data from two alternative plasma guns will be evaluated to determine if a gun down-selection can be made.

A designed experiment will be performed using one alternative plasma gun to refine and validate the as-sprayed surface roughness model predictions.

A method for performing APS repair of new-make TBC will be specified.

Nondestructive TBC Thickness Measurement

Metallographic measurements of bond coat thickness on specimens with eddy current measurements using the flexible probe system will be correlated.

Compound curvature specimens will be built.

Nondestructive TBC Evaluation

Fluorescent penetrant inspection capability for parts will be determined.

Acquisition of laser ultrasound data for flat coupons will be finished.

Laser ultrasound data on the ATS cascade nozzle will be acquired.

The moduli measurement task with CNRC/IMI will be completed.

Technology Application

The process for applying APS 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 2.2.5.2 (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 in ATS applications. An electron beam (EB) 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 to determine the role of TBC thickness on stress development and failure mode in high thermal gradient conditions, the failure modes of various TBCs of different microstructures and deposition techniques, the role of number of cycles and hold times at high temperature on TBC failure mode, and the role of bond coat composition and roughness on TBC life and failure mode. 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.

Progress for this Quarter

Electron-Beam High Thermal Gradient Tests

The fourth CMAS tophat was tested under conditions that produced partial CMAS infiltration into the TBC. A small hot spot was observed in the region of highest CMAS concentration after 21 two-minute cycles. TBC spallation occurred in this same region after 22 cycles. Testing was terminated and the sample was removed for destructive evaluation.

Thermal conductivity measurements were begun on the first fillet tophat. Special sample holders were fabricated for the curved fillet samples. The new holders were shown to produce no measurement error by comparing the thermal conductivity of curved metal foils measured in the new sample holders with that of flat metal foils measured in the conventional way. A second fillet tophat was manufactured and instrumented.

Cascade Nozzle Evaluations

(A) Heat transfer test nozzles

Evaluations were completed. A TBC spall parallel to the airfoil chord on the suction side of Nozzle #30 was observed visually during testing. Metallographic inspection revealed that this spall occurred to the layer depth where additional TBC was added to the suction side of the airfoil by a secondary application. The coating microstructure at the interface between the primary and secondary TBC layers exhibited a distinct plane of weakness in the coating. The creation of the spall was found to coincide in time with the passage of a transient combustor hot streak. It is proposed that the spall resulted from the interaction of the transient thermal stresses and the weak layer in the coating.

(B) LCF test nozzles

Low cycle fatigue testing was completed on a second set of nozzles. TBC spallation initiated in the same locations as on Heat Transfer Nozzle #30. The spalls grew during subsequent cycling, eventually extending across the airfoil leading edges. These nozzles were coated using the same robot program and coating process as that used for Nozzle #30, implying that the same damage mechanism occurred in both tests. Destructive evaluations will be performed following rig disassembly and instrumentation removal.

Plans for Next Quarter

Electron-Beam High Thermal Gradient Tests

Fillet TBC endurance samples will be tested at full ATS conditions until 100 hours and 2500 cycles have accumulated or a TBC hot spot is observed.

The fourth CMAS sample will be destructively evaluated.

The 13 μm IR pyrometer for measurement of TBC surface temperature will be installed and tested.

Cascade Nozzle Evaluations

The LCF cascade nozzles will be prepared for destructive evaluation, which will occur in 4Q98.

Technology Application

Durability of the baseline TBC in an environment simulating that of the ATS baseline 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 (GTTTDD) TBC Design Data and Life Analyses

Objective

Thermomechanical 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 two TBC systems will be evaluated in order to estimate the TBC life under the ATS gas turbine conditions. This will be accomplished by furnace cycle testing TBC systems using a series of dwell times per cycle (0.1 to 20 hours/cycle) and dwell temperatures (1038°C-1148°C, 1900°F -2100°F), and incorporating the results into an existing cumulative damage model. Accelerated testing at temperatures below 1038°C (1900°F) will be accomplished using a tensile thermomechanical fatigue test that superimposes cyclic mechanical strain upon the cyclic thermal strain. In support of the modeling approach, microstructural features of the bond coat and ceramic top 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 as a result of variations in TBC microstructure, and can therefore lead to design inaccuracy. Various 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

A detailed test plan was developed to quantify the life and properties of various TBC systems needed on ATS parts. A total of 13 TBC-substrate systems were selected and prioritized for testing in 1998 and 1999. The relative contributions of time-dependent (oxidation) damage and cycle-dependent (fatigue) damage to ultimate failure of the TBC will be evaluated through mechanical tests and metallurgical evaluations. Mechanical tests include thermomechanical fatigue, compression shear, tensile, ballistic impact, and hardness tests. Thermomechanical 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.

Fabrication of test specimens from nine of the thirteen TBC-substrate systems began. Specimens were machined from René N5, GTD111, GTD222, and Hastelloy-X alloys. Two types of specimen were prepared: 1.00-inch diameter × 0.125-inch thick buttons and 7-inch long × 0.250-inch thick TMF bars. All GTD111 and GTD222 specimens were overaluminided using a NiAl coating to protect the substrate metal from oxidation during high temperature testing.

<u>Furnace Cycle Test</u>

Furnace cycle testing at 1038°C (1900°F) continued for two TBC systems, using dwell times of 0.1, 0.75, and 10 hours per cycle. To date, 4350, 1860, and 180 cycles have accumulated on these samples, respectively. Some specimens were removed at intermediate times for tensile testing and microstructural analysis. Two TBC systems are also being tested at 1093°C (2000°F) using a dwell time of 20 hours per cycle.

<u>Thermomechanical Fatigue Testing</u>

The thermomechanical fatigue (TMF) testing will be 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. 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. Vendor TMF testing capability was verified using an uncoated test specimen.

Thermal Conductivity

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

Variation in TBC thermal conductivity caused by differences in raw materials will be evaluated. Ceramic powder from three suppliers was used to prepare test samples. Some samples will be minimally aged and others will be aged at 1315°C (2400°F) for 100 hours prior to measurement.

Plans for Next Quarter

The machined and aluminided test specimens will be coated using processes developed for specific ATS components. Some coated specimens will be furnace-aged at various temperatures and times prior to testing.

Furnace Cycle Test

Testing at 1038°C (1900°F) and 1093°C (2000°F) will continue. Samples tested at 1093°C (2000°F) in 1997 will be examined using laser ultrasound NDE and tensile testing.

Thermomechanical Fatigue Testing

The ignitor furnace will be calibrated for each type of TBC to be tested. Furnace calibration, data acquisition, and TMF software performance will be checked using a coated dummy specimen prior to starting the actual tests.

Thermal Conductivity

The effect of gas pressure on the thermal conductivity of the samples used in the aging studies will be estimated.

The thermal conductivity of TBC sprayed with powders from the various suppliers will be measured.

Technology Application

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

Section 2.3 (CC) COMBINED CYCLE INTEGRATION

Section 2.3.1 (CCUA) Unit Accessories

Objective

Development of four new unit accessories—fuel heating, cooling-air cooling, steam cooling, and clearance control—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 ATS gas turbine. The clearance control system also enables the turbine to operate at a higher efficiency than would be possible without it. The exhaust diffuser will be designed so that maximum possible pressure recovery will be realized, thus increasing the performance of the ATS gas turbine.

Designs of remaining accessory systems will be conventional.

Progress for this Quarter

Cooling-Air Cooling System

Toward the end of 1Q98, the interconnect piping design dictated a change in the skid configuration so that the skid layout would better suit interconnect piping design needs. During 2Q98, GE Engineering worked with the supplier of the cooling-air cooling system to develop a new skid layout that is almost complete. A review with the supplier and GE Engineering is scheduled for early 3Q98. Detail design of the system components was begun. A decision was made to use the cooling-air cooling system to provide air for the gas turbine combustion purge air system. As a result, the cooling-air cooling system layout and component design are taking this added requirement into account.

Steam Cooling System

The design specification was completed and an order placed for the steam cooling system filter and filter vessel for the ATS gas turbine. Detailed definition of the system valves was developed during 2Q98, with completion expected in 3Q98 so that an order for the valves can be placed by 4Q98. Development work progressed on the steam flow measurement portion of the steam cooling system, although most of the steam flow measurement system will be developed during 3Q98. The final production process and interface drawing (P&ID) for the steam cooling system was developed during 2Q98, with completion expected early in 3Q98.

Clearance Control System

The clearance control skid was built and shipped to the GE gas turbine test facility in Greenville, SC, in 1Q98. In 2Q98 the operation of the skid was verified during the initial FSNL test of the ATS gas turbine. The skid was first operated independent of the gas turbine at full flow, temperature, and pressure in a closed loop configuration in order to verify that the system could operate satisfactorily with the test facility control system, lube oil system, and cooling water system. During these tests, the clearance control skid performed extremely well. The clearance control skid also performed very well in conjunction with the gas turbine during the FSNL test. The skid met its design requirements reliably, and test results verified that the gas turbine clearances were affected by the clearance control system as expected.

Exhaust System

Development of the exhaust diffuser focused on the interface between the diffuser and the steam cooling piping systems that penetrate the diffuser shell. The piping will penetrate the straight cylindrical portion of the diffuser, which was lengthened in 2Q98 to better accommodate the large quantity of steam cooling piping. In addition, preliminary design work was done on the interface between the piping and the diffuser which will have to take into account the relative thermal growth of both the piping and the diffuser. It was decided that the exhaust diffuser design would be one of the first unit accessories to be designed in accordance with a GE quality effort called "design for six sigma" (DFSS), which is a rigorous process utilizing statistical design tools intended to achieve design work of the highest quality and highest reliability attainable.

Plans for Next Quarter

Cooling-Air Cooling System

The skid configuration will be completed and the detail design of the system components will be underway. A design review between GE Engineering and the supplier will be held to review the skid and component design.

Steam Cooling System

The steam cooling system P&ID will be completed. The definition for the valves and flow meters will be completed, and outline drawings will be issued to the supplier so that detail design of the valves and flow meters can begin in 3Q98 and 4Q98.

Clearance Control System

The clearance control system operated to the design specifications during the initial 9H FSNL test. Initial operation of the clearance control system during this test did reveal some areas that may prove capable of improvement: the system charging circuit and the system heat exchanger/cooling water circuit. This possibility will be studied during 3Q98. The study, which may include further testing of the skid without the gas turbine, will be conducted in two phases: first, improvements to the system prior to the next 9H gas turbine FSNL test; second, improvements to the production system that will be used in the field for gas turbine FSFL operation. The second phase is likely to take place during 4Q98 and 1Q99.

Exhaust System

The detail design of the exhaust diffuser will begin in 3Q98, with completion expected early in 4Q98. Also during this time, fabrication design details will be developed with the diffuser supplier so that the first exhaust diffuser can be built and shipped by the end of 1Q99.

Technology Application

Development of the cooling-air cooling system, the steam cooling system, the clearance control system, and the exhaust diffuser system 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 systems will continue in order that the ATS gas turbine 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

Control algorithms for the gas turbine were coded into control system programs to support the initial 9H FSNL test. Control loop dynamic studies were performed to support this test, including: gas turbine clearance control, variable guide vane control, fuel control, and startup and shutdown sequences. The prototype control panel was tested as part of the FSNL test. Development of algorithms for the protection of the H technology gas turbine continues, focusing particularly on the protection of hot gas path components.

Plans for Next Quarter

Study of control loop dynamics will continue, expanding the simulation to include the steam turbine and the HRSG to form a combined cycle control system. Software algorithms and sequence logic for the gas turbine will continue, with emphasis on the steam cooling system and coordination with the steam cycle operation. Control program coding for the steam turbine and HRSG controls will be started. Verification of the control programs will continue, using equipment models and actual control panels.

Technology Application

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

The reliability goals were established for the plant and were allocated to the major systems and to systems across the complete combined-cycle plant for both the 9H and the 7H. These were recorded in the Design Memo for both the 9H and 7H.

The specific system level reliability goals were provided to design teams across the entire combined-cycle plant in a Reliability Goal Packet published for each system. This document provides the design engineer with basic information about the reliability design goal, current GE experience, the reliability engineering techniques that will be utilized, and a review of the Design For Reliability process. These Reliability Goal Packets were also provided to vendors responsible for specific systems as technical requirements for the system design.

Initial reliability assessments of several accessories systems were performed using reliability block diagrams. These systems include: clearance control, atomizing air, cooling-air cooling, and several balance of plant subsystems.

FMEAs of the rotor steam delivery circuit continue to be performed. A component FMEA was completed on the spoolies and started on the bore tube.

A flange-to-flange safety review of the 9H was completed prior to the FSNL test This included an assessment of the FSNL vibration protection reliability system. A safety review of the Kopflex coupling that resulted in new procedures and equipment was completed.

Plans for Next Quarter

The remaining Reliability Goal Packets will be distributed to the final design teams. Reliability assessments for several critical systems will be started, including: fuel heating, steam cooling, hydraulic, lube oil, compressor, turbine, and combustion.

Component FMEAs will be started on the bore tube, radial tube, and elbow in the rotor steam delivery circuit. System FMEAs will be started on the exhaust system and rotor steam delivery circuit.

A safety review of the steam piping on the 9H will be completed. Additional safety reviews for the fired and hazardous gas detection systems and enclosure will be started.

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.

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

Extensive modifications of the steady state system performance model (SSPM) were concluded as part of a quality initiative. The focus of this effort was both increased reliability of the numeric processes and reduced execution time. The current benefits of this effort are a reduction in the number of failed points and a reduction in computing time. A fuel heating system optimization study was initiated using "design for six sigma" (DFSS) methodology to evaluate the life cycle cost impact of various fuel heating schemes. Work on improving speed and convergence of the SSPM is nearing completion. Work continued on automating the design point calculations and modifying them for the continuing configuration changes of the combined cycle system.

Machine operability was reviewed with heat recovery steam generator (HRSG) vendors. Development of the thermal dynamic model (TDM) on a new platform is close to completion. Steady state verification of the new model is completed. The new TDM incorporates the most recent configuration and plant data, as well as some of the new controls logic. Its structure is suitable for later use as a simulator for controls hardware testing. The gas turbine model used in this structure is already verified against the results of the initial 9H FSNL test carried out in 2Q98. Verification of a more detailed gas turbine model is underway.

Plans for Next Quarter

Optimization studies for the combined cycle subsystems will continue. Additional automation of the design point calculations will be made as part of a quality project in a continuing effort to develop a standard design point/off-design automation package. Modifications of the SSPM as part of a quality initiative will continue. Improvements and extensions to the performance model will continue to enable automation of design point calculations. The automation of the design point calculations activity is being folded into a general design-to-cost activity as a quality project.

Machine operability reviews will continue, with emphasis on startup and shutdown procedures. The TDM, including the new controls logic, will be completely tested on the new platform and ported into the real-time simulation environment. Startup and shutdown scenarios will be performed on the TDM. System operability limits, especially as response to load change demands or grid upsets, will be investigated in more detail. The new TDM will also include the latest transient cycle deck model with turbine heat soak/release capabilities.

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.

Progress for this Quarter

Test stand construction was completed, system checkout, and instrumentation and control installation were accomplished, and the 9H gas turbine assembly was completed, allowing it to move to test.

Initial FSNL testing of the 9H turbine was completed successfully. All planned test runs were made and test objectives were met. Data from extensive instrumentation did not identify any major concerns with operation or performance of the unit.

Plans for Next Quarter

During the next reporting period, the 9H turbine will be transported from the test stand to the factory, and teardown in preparation for the next FSNL test will begin. Further analysis of instrumentation data from the first FSNL test will be performed.

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 NOx 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

There was no activity associated with this task under the ATS Phase 3 Cooperative Agreement during the current reporting period.

Plans for Next Quarter

There is no activity planned for this period.

Section 2.6 (DE) Pre-Commercial Demonstration

This task is deleted.

Section 2.7 (PM) Program Management

Objective

Within 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 CRD and 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, that 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 Agreements 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 Program Review was held at GE Aircraft Engines, Evendale, OH, in order to tour the full-scale combustion development test stand (A2), and the full-scale nozzle cascade test stand (A3).

Plans for Next Quarter

A Program Review is scheduled to be held at the GE Power Systems manufacturing and test facility in Greenville, SC, in order to see the 9H gas turbine and test stand and the gas turbine production facility.

Work will continue on the ATS Phase 3R Continuation Application input, with a cost-to-complete for the remainder of Budget Period 2 and for Budget Periods 3 and 4.

SECTION 2 TECHNICAL PROGRESS REPORTS: COMPLETED TASKS

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

To achieve ATS performance goals, a four-stage turbine was designed. 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 is to provide thermal and mechanical design and analysis support for rotor components of the ATS gas turbine. Analyses are run to determine temperature, displacement, and stress distributions for various components of the ATS gas turbine rotor. Initial designs and concepts are 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 will be used to robustly design an ATS gas turbine rotor that meets cycle life requirements.

Section 2.2.2.3.2 (GTFFTR) Wheel Forging Residual Stress Analysis

Objective

The objective of this task is 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 may have an effect on fatigue life and will affect residual displacements. The effect on residual rabbet deflections is particularly important since this may affect rabbet opening/closure as well as rabbet loading and local plasticity. If residual stresses turn out to be significant in the ATS machine (IN718) as well, they will have to be included in the design calculations. The residual stress calculation will be done on the 7F wheel first to correlate the analysis with available test data. The procedure will then be applied to the ATS wheels.

Progress for this Quarter

This task 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 remain after the aging process, the residual stresses will be included in the design calculations.

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 here 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 is to obtain robust bucket designs that are minimally sensitive to manufacturing tolerances and will therefore meet all life requirements.

Progress for this Quarter

This task was completed in 4Q97.

Technology Application

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

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-stage 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 lives 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 2.2.2.5.1 (GTFFTS) Turbine Stator Robust Design

Objective

The objective of this work is to develop and apply robust design methods for the development of steam-cooled components of the advanced gas turbine. The goal of this effort is 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 the robust design studies described above 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 has been applied by the design engineers to other components of 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. One of these features was 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 2.2.3.1.1 (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 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 2.2.3.4.1 (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 will be constructed that will be identical to the one tested previously except for the addition of the new mixing rib geometry. This passage will be evaluated in the full-scale rotational test rig over the range of dimensionless parameters present in the ATS gas turbine.

Plans for Next Quarter

This task was completed in 1Q98.

Technology Application

The new turbulator and rib design, which has to-date only been demonstrated in small-scale tests, is being employed to reduce the bucket cost and to yield a more robust design with improved performance at high Buoyancy numbers. This design will be validated by the full-scale data to be 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 2.2.3.5.1 (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 task objective is 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.

Plans

This task was completed in 1Q98.

Technology Application

The results of the tests conducted as part of this task were used directly in the design of the second-stage bucket for the ATS gas turbine.

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 changed 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 will also be 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 that was 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 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 those from open literature correlation predictions (Metzger). The new data improved the design of the first-stage nozzle internal cooling scheme.

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 was characterized using flat plates tested in an atmospheric wind tunnel. An advantage of flat plates over airfoils is that TBCs can be easily applied 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 on two forms within the design of the turbine airfoils. First, tests which 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 upon the nonlinear effects of surface roughness, especially as the nozzle design could not rely upon 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, 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 2.2.4.2 (GTMTSO) Oxidation Due to Steam

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

This task was designed to evaluate the static behavior of turbine materials in a steam environment in order to take into account the introduction of steam cooling.

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

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

This task evaluated potential airfoil coatings in environments that reflect planned ATS 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 examined potentially less expensive materials for use in blades and vanes in the latter stages of the ATS compressor. These evaluations of alternate materials were based on results of tests of mechanical properties, with emphasis on HCF properties. For the materials that were selected, tests of critical properties were conducted under ATS-specific conditions. Component tests of select parts were conducted for life verification purposes and establishment of final manufacturing parameters.

Plans

This task was completed in 1Q97.

Technology Application

This task characterized 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 (VGV) bushings and thrust washers was gathered to ensure a robust and reliable design. Testing was conducted to confirm materials selections, cover any parameters outside of existing data, and gather data for new materials.

Plans

This task was completed in 2Q97.

Technology Application

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

Section 2.2.4.9 (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 task was completed in 1Q98.

Technology Application

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

Section 2.2.4.12 (GTMTST) Turbine Structures Materials and Processes

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

This task contributed to the characterization of turbine structure materials in test conditions that reflect service environments.

Section 2.2.4.13 (GTMTSH) Turbine Shells

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

This task contributed to the 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 were developed for the ATS turbine utilizing seal technology developed for aircraft engine components where applicable. The technology will be evaluated using developmental hardware and samples.

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.4.14.1 (GTFFTSESV) 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 is 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 is 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 are required to help meet the ATS combined cycle efficiency target. The other objective of this task is to develop and test transition piece cloth seals that meet both leakage performance and life requirements. Specifically, advanced cloth seals will be developed for the transition-piece/first-stage-nozzle junction. Life consistent with the prescribed inspection interval is required.

Progress for this Quarter

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 brush seals were used in the first machine by nesting the brush seal within the labyrinth seal packings. A slot will be machined in the labyrinth seal to accept the brush seal. On subsequent machines, the steam gland can be shortened to take advantage of improved sealing and reduce the manufacturing cost of the steam gland.

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 available data show 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.