#23

GE Power Systems

Utility Advanced Turbine Systems (ATS) Technology Readiness Testing

PHASE 3R

Technical Progress Report

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ACRONYMS USED IN GE ATS REPORT

ACC - active clearance control

AEC - Automated Eddy Current

ANSYS - *finite element software*

APS - air plasma spray

ATS - Advanced Turbine System

AWS - aft wheel shaft

CAC - cooling-air cooling

CAD - computer-aided design

CC - compressor case

CDC - compressor discharge case or casing

CDD - compressor discharge diffuser

CFD - computational fluid dynamics

CMAS - calcium-magnesium-aluminum-silicate

CMM - coordinate measuring machine

CNC - computer numeric control

CNRC - Canadian National Research Council

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

DTA - differential thermal analysis

DTC - design to cost

DVC - dense vertically cracked

EA - Environmental Assessment

EB - electron beam

EDM - electron discharge machine

EDR - electronic data release

EIS - Environmental Impact Statement

EPRI - Electric Power Research Institute

FBD - Free Body Diagram

FCP - fatigue crack propagation

FCT - furnace cycle test

FEA - finite element analysis

FEM - finite element model

FETC - Federal Energy Technology Center

FFT - Fast Fourier Transform

FMEA - failure modes effects analysis

FONSI - Finding of No Significant Impact

FPI fluorescent penetrant inspection

FPQ - first piece qualification

FSFL - full speed, full load

FSNL - full speed, no load

GASP - gravity-assisted shot peening

GEAE - GE Aircraft Engines

GEPG - GE Power Generation

GEPS - GE Power Systems

GTAW - gas tungsten arc weld

GTCC - gas turbine combined cycle

HCF - high cycle fatigue

HIP - hot isostatically pressed

HP - high-pressure

HRSG - heat recovery steam generator

HVOF - high velocity oxy-fuel

IGCC - integrated gasification combined cycle

IGV - inlet guide vane

IP - intermediate-pressure

IP&D - process and interface drawing; process and instrumentation drawing

IR - infrared

IR - infrared

IT - Inverse Time

KCC - key control characteristic

KCP - key control parameter

KNP - key noise parameter

LCF - low cycle fatigue

LCVT - liquid crystal video thermography

LH - lower half

LUT - Laser Ultrasound

NDE - nondestructive evaluation

NDT - nondestructive testing

NEPA - National Environmental Policy Act

ORNL - Oak Ridge National Laboratory

P&ID - process and interface drawing; process and instrumentation diagram

QDC - Quality Data Collection

QFD - quality function deployment

RAM - reliability, availability, and maintainability

SEM - scanning electron microscopy

SLA – stereo lithography apparatus

SSPM - steady state performance model

SSRT - slow strain rate tensile STP - Segment Time Programming

TBC - thermal barrier coating

TBO - time-between-outages

TC - thermocouple

TCP - Tool Center Point

TDM - thermal dynamic model

TDS - thermal dynamic simulation

TEM - transmission electron microscopy

TIG - tungsten inert gas

TMF - thermomechanical fatigue

TP - transition piece

UAB - Utility Advisory Board

UG - UniGraphics

UH - upper half

VGV - variable guide vane

VPS - vacuum plasma spray

VSV - variable stator vane

YFT - *fluids analysis software*

SECTION 1 EXECUTIVE SUMMARY

The overall objective of the Advanced Turbine System (ATS) Phase 3 Cooperative Agreement between GE and the U.S. Department of Energy (DOE) is the development of 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. Note: Information specifically related to 9H production is presented for continuity in H program reporting, but lies outside the ATS program.

This report summarizes work accomplished in 2Q99. The most significant accomplishments are listed below:

9H-Specific

- Completed assembly of the 9H Full Speed, Full Load (FSFL) pre-shipment gas turbine, transported it to the test stand, and initiated preparation for testing.
- Completed test stand modifications to meet 9H FSFL pre-shipment test requirements.

9H/7H-Common Technology

- Completed 9H combustor testing at the GEAE-Evendale, OH combustor test stand and initiated conversion of the stand to the 7H configuration.
- Installed the turbine rotor rig in the GEPS Engineering Development Lab test stand and initiated preparation for testing.
- Continued incorporation of 9H lessons learned into the 7H machine design.

7H-Specific

- Completed assembly of the 7H compressor rig at GEAE-Evendale, installed the rig in the GEAE-Lynn, MA test facility, and initiated mechanical checkout in preparation for the compressor rig test program.
- Continued test cell preparation activities for the 7H FSNL test, including test plan reviews and long-lead-time item procurement, and completed test stand readiness review.
- Continued manufacturing of all 7H gas turbine components in preparation for the FSNL test.

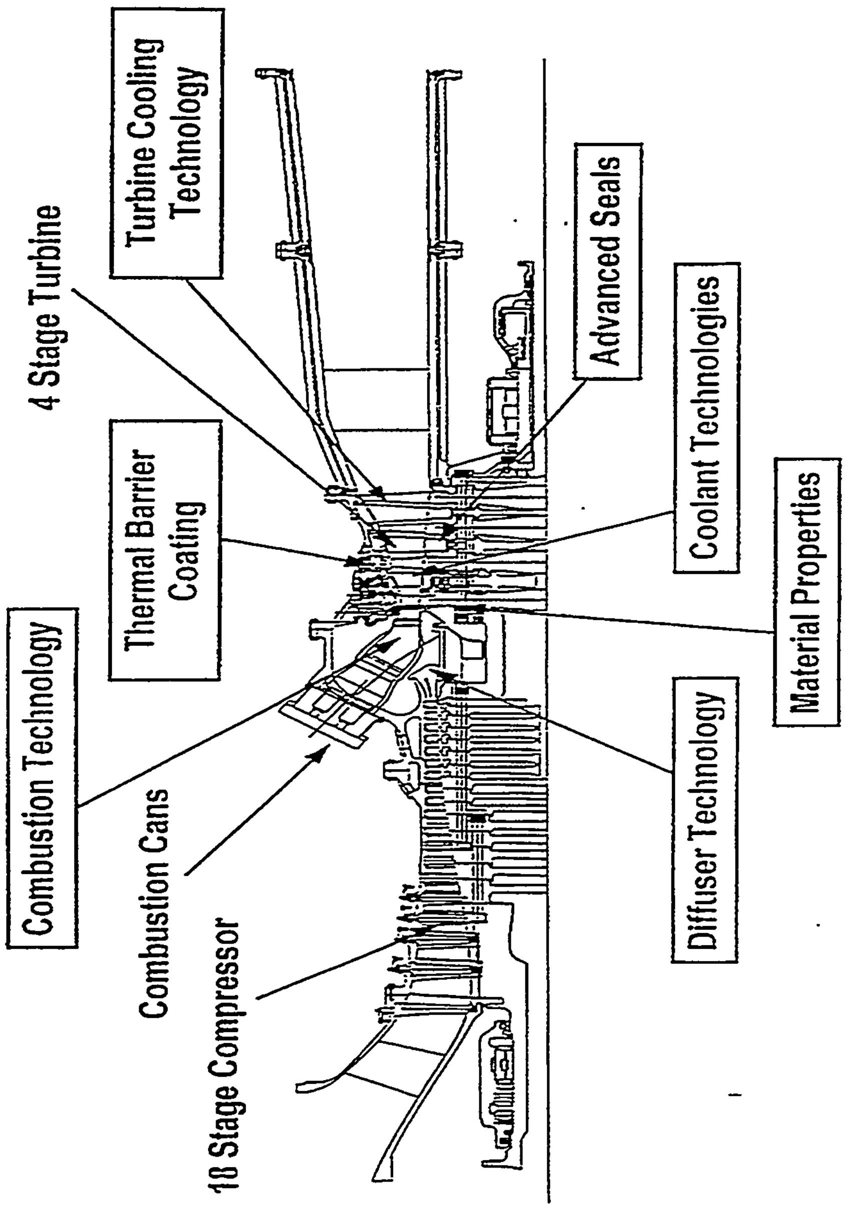

Figure 1-1. Schematic of the H gas turbine cross section

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

Section 2.2 (GT) GAS TURBINE DESIGN

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

Section 2.2.2.1 (GTFFCP) Compressor Design

Objective

The objective of this task is to design 7H and 9H compressor rotor and stator structures with the goal of achieving high efficiency at lower cost and greater durability by 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

The 7H aerodynamic design was completed for the airfoil stages and aeromechanics evaluation of the airfoils was also completed. The 7H compressor flowpath incorporates lessons learned from 9H rig and FSNL testing. The detail airfoil stress analysis, including vibratory and static finite element analysis for all blading, was completed. The final machining drawings for all rotor blades and stator vanes have been issued.

The blade supplier was down-selected based on a combination of technical ability, cost, and schedule commitment. All forging materials were purchased. The manufacturing for rotor blades and stator vanes was started and is in various stages of forging or machining. The projected delivery for all blading will be in 3Q99.

The compressor rotor design analysis, including two-dimensional heat transfer and stress analyses, low cycle fatigue, high cycle fatigue, fracture mechanics, creep, burst, rotor dynamics, bolt sizing, rotor structure and rabbet integrity, blade retention, and dovetail slot sizing, was conducted to support the release of forging and machining drawings.

The final drawings for forward and aft stub shafts and all wheels were issued. Rotor suppliers were down-selected based on a combination of technical ability, cost, and schedule commitment. The forgings for forward and aft stub shafts and all wheels were purchased. The manufacturing for forward stub shaft, and stages 6 through 16 wheels, was started. The projected delivery of all rotors will be in 3Q99.

The 7H compressor rig test program was initiated at the GEAE-Lynn, MA test facility on June 30, 1999. The test will include six test phases and will last six to eight weeks.

Plans for Next Quarter

All detail compressor rotor three dimensional finite element analysis to support the drawing release will be completed. All compressor parts including all blading and rotor components will be delivered to GE. The compressor assembly will start in the late 3Q99 and completed in mid 4Q99.

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

Tests to provide thermal characterization of the combustion system components were conducted in the GEAE Stand A2. The data obtained were used to calibrate the finite element thermal and stress models constructed to perform parts lives predictions. The resulting predictions indicated that all part life goals will be met for the combustion system. In addition, the testing was used to optimize combustor cooling.

Testing in GEAE Test Stand A2 was temporarily suspended so that the stand could be reconfigured for 7H testing in 3Q99.

The 7H full speed no load (FSNL) combustion system drafting was completed and all parts were put on order at suppliers. The initial gas turbine set of transition piece aft frames continued to have casting problems, but a recovery effort was initiated and the majority of the frames were poured successfully. The first experimental transition piece was delivered to A2 stand, and the production transition piece set will be delivered to the gas turbine assembly area early in 4Q99.

Plans for Next Quarter

Testing will resume in GEAE Stand A2 in the 7H configuration. Initial testing will include emissions, combustion dynamics, and stability mapping. Development will resume to obtain product NOx margin. The 7H FSNL combustion system fabrication will be completed and the assembly process into the gas turbine initiated.

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

All dovetail drawings have been issued.

All structural and steam delivery component drawings have been issued.

The forward turbine rotor parametric subsystem model has been running with multiple configuration iterations completed. The aft turbine rotor parametric subsystem model has been running with multiple configuration iterations completed. The full turbine rotor parametric system model has been running with multiple iterations completed. The layout and system model runs are now frozen for preliminary life analysis.

Structural component machining is well underway. The lead component is the stage 3 turbine wheel, currently on the broach machine in Greenville.

The turbine rotor steam delivery system risk release review was completed. The Action Items generated are being worked by their priority.

Steam delivery component machining is well underway. The cast elbows were completed and shipped for machining. The cast manifolds are on schedule to ship the first castings early next quarter.

Plans for Next Quarter

Turbine rotor structural risk release review will be completed.

All turbine rotor structural components will be machined and completed.

Steam delivery components will be machined and completed.

All assembly drawings will be issued.

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 computational fluid dynamics (CFD), and the results of the analyses will provide the basis for design modifications if necessary.

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

Progress for this Quarter

A CFD simulation of the latest 7H and 9H supply bore tube designs was completed and documented. Starting with a description of the CFD model common to both designs, boundary conditions and results for each scenario were derived. The combination of the different rotational speeds in the two designs and the identical scroll concept and flowrates leads to an inlet flow in the 7H with an underswirl that is not present in the 9H. The result is markedly different flow swirl angles in the bore tube annulus and correspondingly different pressure drop profiles

The hydraulic performance of the new design is better than that of the previous 9H design. Despite the fact that the previous design operated at a lower flow, the pressure drops at the entrance and past the strut are lower in the current design. The value of the swirl that develops just upstream of the strut agrees well with the predicted value for the previous 9H bore tube design. The passage of the flow around the strut causes a drop in the swirl angle, and frictional losses downstream of the strut cause a slow decay in the flow swirl angle.

The entrance pressure drop is slightly higher in the 7H than in the 9H. This is expected, as the flow enters with a relative swirl in the 7H, whereas in the 9H, the flow is perfectly radial (in the relative frame of the rotor). The difference, however, is slight. On the other hand, the pressure drop past the strut is substantially lower in the 7H design than in the 9H design because of the lower flow swirl angle in the 7H configuration.

Plans for Next Quarter

The design of the inlet bore tube is currently undergoing significant design modifications. A new CFD analysis of the emerging configuration is very likely.

Technology Application

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

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

Activity on this project is on hold.

Plans for Next Quarter

There are no plans for 3Q99.

Technology Application

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

Section 2.2.2.3.6 (GTFFTR) Rotor Component Flow Tests

Objective

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

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

Progress for this Quarter

The test program in 1999 is focused on quantifying the flow stability in key components in the rotor steam-cooling flow path. This focus is the result of a concern that coherent flow instabilities (i.e., tones), coupled with system natural frequency response could accelerate wear, and fatigue of system parts. Two components in the steam circuit have been identified as warranting investigation—the spoolie couplings and the bore tube.Testing of the spoolies to determine the presence of flow-generated instabilities is complete. Seven dynamic pressure transducers were installed at locations upstream and downstream of spoolie joints in the manifold and in the bucket. Three spoolie joints were tested in the spoolie test stand: the first joint connects the axial tube to the inlet of the manifold, the second joint connects the exit of the manifold to the bucket tube, and the third joint connects the bucket tube to the inlet of the bucket. For testing, six flowrates were chosen to simulate the steam flow at the range of gas turbine operating conditions. Scaling the flow settings from machine to model test was done by matching the Mach number of the machine in the model test. Dynamic data were taken from each pressure transducer at each of the six flow settings. The data were reduced and plotted to show the spectral content, amplitude, and frequency of each pressure transducer at each flow setting. Additional tests were conducted to determine the effect of tube or joint misalignment. In the second part of this test, the axial tubes were misaligned by 5 degrees, and the tests were repeated to check for leak tolerance.

In general, all of the flow conditions tested were very quiet and had only low amplitude pressure signals. The data will be used as input for mechanical vibration analysis. Assuming there is no additional testing required for the mechanical analysis, the spoolie tests are complete.

Fabrication, instrumentation, and installation of the bore tube are complete. A series of shakedown tests has been completed. In the shakedown tests, the model withstood all flow conditions, the full range of design flow and Mach numbers was achieved, and inlet flow swirl angles were controlled and set over the range of design conditions. At this point in the testing cycle work was stopped in order to enable Design Engineering to evaluate a new bore tube design. Currently there are no plans to restart testing of this bore tube.

Plans for Next Quarter

None.

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

The 7H stage 1 bucket aeromechanical analysis was completed, and the bucket internal design definition continued for release to the tooling vendor. The 7H stage 2 bucket internal core definition was approved for release to the tooling vendor. Detailed thermal-mechanical analysis was initiated to define the stage 2 bucket external configuration. The 7H stage 3 bucket airfoil stack aeromechanical analysis was initiated. The 7H stage 4 bucket tip shroud analysis was initiated in order to define the final tip configuration.

Plans for Next Quarter

Detailed analysis to continue on all buckets. Casting producibility trials are planned in order to confirm design geometries.

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 steady-state liquid crystal techniques in a blade tip cascade.

Progress for this Quarter

The new bucket tip cascade test rig was received and assembled, and the initial verification tests were completed. There was a reasonable match between predicted Mach number distributions and pressure measurements made in the cascade. Pressure measurements were made at the shroud, tip, and midspan with various blade tip clearances and with and without blade tip treatments. Heat transfer coefficients were measured on approximately 75% of the flat surface of the blade tip with and without tip treatments. A letter report containing initial smooth results was sent to Design Engineering.

Plans for Next Quarter

All data taken will be reduced and analyzed and results reported. Further necessary tip tests will be defined.

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 2.2.2.4.7 (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

Previous work on this task conceived the 3X-scale model design for the turbine bucket platform cooling side cavity region, fabricated the model, and performed the basic testing required to qualify the test technique as used in this case. The previous efforts also completed a test matrix for the prototype platform cooling design, reduced the heat transfer coefficient distributions, and reported results scaled up to engine conditions for design boundary conditions.

Experimental efforts in the present reporting period have remained on hold pending the completion of the improved platform cooling design; no test section modification or testing has occurred in this period.

The CFD analysis of the platform cavity region flow and heat transfer has been completed, and the results provided to the GEPS design engineering team.

Plans for Next Quarter

During 3Q99, it is expected that Design Engineering will select a revised platform cooling design and that modification of the existing model test section will be completed in preparation for validation testing.

Technology Application

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

Section 2.2.2.5 (GTFFTS) Turbine Stator Design

Objective

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

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

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

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

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

Progress for this Quarter

Baseline lives, leakages and coolant system requirements were established for the 7H stage 1 and 2 nozzles via detailed heat transfer, flow and 3D finite element analyses. Conceptual/Preliminary Design Reviews were held for the 7H stage 1 and 2 nozzles. Casting definition was released for the 7H stage 2 nozzle (full) and 7H stage 1 nozzle (partial). Prototype casting trials are underway for the 7H Stage 1 and 2 nozzles.

Plans for Next Quarter

Further analyses will be conducted to complete 7H stage 1 nozzle airfoil casting definition, and tooling will be initiated for both the 7H stage 1 and 2 nozzle castings. Definition for 7H Stage 1 and 2 nozzle long-lead items, including steam covers and airfoil cooling inserts, will be released. Analytical activity on the 7H stage 1 and 2 nozzles will continue, to optimize component lives and air/steam circuit performance. Prototype airfoil casting trial efforts will continue on the 7H stage 1 and 2 nozzles.

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

Compressor Case

Machining operations were completed at the suppliers for the inlet, mid-compressor (CC), CDC, inner barrel and VGV components. Inlet, mid-compressor (CC), CDC and VGV components successfully passed First Piece Qualification (FPQ). The results of the quality audit were excellent and all components are either at Greenville or in transit. FPQ for the diffuser and inner barrel is scheduled for the second week in July. All component assembly drawings and Bills of Material were issued. Detailed finite element life analysis has been initiated.

7H Exhaust Frame and Diffuser

The exhaust frame fabrication, heat treatment, and machining were completed in 2Q99. The forward diffuser fabrication was also completed during this time period. Instrumentation of the frame for the FSNL test was also initiated.

The 7H exhaust frame has incorporated "hard pack" insulation (similar to production designs) since aft shaft cooling is no longer required. The inner barrel insulation packs were placed on order in March and the outer barrel packs ordered in April. The inner barrel & strut insulation packs were shipped to the supplier at the end of the quarter.

Several analyses are in progress as a result of action items from the Tollgate 4 review in February. These analyses include the cooling/purge flow analysis and transient thermal analyses of the diffuser, frame and assembly components.

7H Steam Gland

Instrumentation definition drawings were defined and issued. Machining operations have started and are scheduled to be completed early in 3Q99. Brush seal test plans were completed, and hardware procurement has begun. 2D finite element transient heat transfer and life analysis have been initiated.

No 2. Bearing Housing

Instrumentation, assembly and seal drawings were issued. Machining operations at the supplier have been initiated. FPQ is scheduled for early 3Q99.

Plans for Next Quarter

Compressor Case

Machining operations and FPQ for the diffuser and inner barrel will be completed. Assembly operations in Greenville will be completed, and the VGV actuation system will be demonstrated. The detailed life analysis will be completed.

Exhaust Frame

7H Exhaust Frame and Diffuser

Instrumentation of the frame and diffuser will be completed. The vendor will finish assembly of the exhaust frame and will ship the frame assembly to Greenville. The detailed transient analysis of the frame and the diffuser will be completed.

7H Steam Gland

The supplier will complete the steam gland machining operations and ship it to Greenville, SC for assembly. The detailed life and horizontal joint bolting analysis will be completed. The brush seal leakage test at CR&D will be completed.

No 2. Bearing Housing

The supplier will complete machining operations of the No. 2 bearing housing and ship it to Greenville, SC for assembly.

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 preparation for the 9H full speed, full load (FSFL) pre-shipment test, and the 7H detail design.

Assembly operations continued to support the FSFL pre-shipment test. The 9H gas turbine assembly was completed and the unit was shipped to the test facility.

Detail design of the 7H is nearly completed, and component hardware manufacture is well underway. Cost, schedule, risk, and performance metrics were reviewed and updated. Tollgate progress was measured and the program successfully passed the preliminary design tollgate review in May, 1999.

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

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, continues to meet to review the merit of system issues and determine whether incorporation of ideas meets system goals.

Cross-section drawings for the 7H were updated, reflecting the preliminary design configuration and interface decisions. Hot and cold cross-sections are now available for use.

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

Plans for Next Quarter

The 7H Detail Design tollgate will be completed. Systems studies and decisions will continue in support of ongoing development. Customer support will continue, ensuring that the final 7H configuration meets the customer's needs. Unit assembly will begin.

Tthe 9H gas turbine will be prepared for FSFL pre-shipment 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 2.2.2.8 (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

9H: The data collected during the first 9H FSNL test for this hardware was analyzed and fed back into the on-base designs. This data was used to improve those first FSNL designs and will be used to complete the balance of non-FSNL tested systems. All on-base piping, turbine base, and electrical designs required for the FSFL pre-shipment test were previously completed. The 9H gas turbine moved to the test stand this month and work is underway to prepare it for the FSFL pre-shipment test. Work continued to complete the documentation package for the unit to ship to the field next year.

7H: Preliminary design work for on-base and external piping design is underway. Preliminary CAD models were created. Lessons learned from 9H activities were incorporated into the 7H design. A first formal design review held for the 7H turbine base, with no major issues nor major action items identified. The turbine base drawings were released this quarter, and an order was placed with the supplier. The balance of the on-base piping and electrical designs continued. Design work is on schedule to support the presently scheduled 12/99 7H FSNL test date.

Plans for Next Quarter

9H: Support the 9H FSFL pre-shipment test at test stand. Complete documentation release of all hardware required for a field installed unit not previously completed nor needed for the FSFL pre-shipment test.

7H: Continue preliminary design and CAD modeling of 7H on-base and external piping hardware. Initiate formal design review of on-base piping package. Incorporate all 9H lessons learned.

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 flange-to-flange gas turbine has been shipped to the Greenville, SC test facility (Test Stand #8) for the FSFL pre-shipment test. The instrumented load coupling was connected to the compressor forward shaft in the factory prior to test stand shipment. The flange-to-flange gas turbine instrumentation hookup and all skids/accessories connections are continuing at the test stand.

The FSFL pre-shipment test Red Flag design reviews were completed. Based on these reviews, there are no problems anticipated to start the test as planned. Action Items were generated in various reviews, and all these action items will be resolved prior to startup.

Plans for Next Quarter

All sensor connections, data acquisition systems, pipings, and skids will be checked out prior to testing.

Technology Application

These are test plans to establish the instrumentation requirements for 7H and 9H FSNL, FSFL pre-shipment, and 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 2.2.3.2 (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 static flow tests and the CFD analyses were completed.

Plans for Next Quarter

The CFD analysis and flow test results will be evaluated and compared.

Technology Application

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

Section 2.2.3.3 (GTETSE) Spoolie Test Program

Objective

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

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

Progress for this Quarter

A high-temperature high-pressure test rig, capable of simulating spoolie performance during service in the H machine was built. A Design of Experiments was developed to determine the effect of steam temperature, joint interference, and degree of angulation of spoolie life.

Seven tests have been completed to date, and the results summarized. Preliminary analysis of results indicate that spoolie life increases with interference and steam temperature.

Plans for Next Quarter

A decision will be made as to whether to conduct additional spoolie tests.

Technology Application

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

Section 2.2.3.5 (GTETIH) SURFACE ENHANCED INTERNAL HEAT TRANSFER

Section 2.2.3.5.2 (GTETIH) S2B Trailing Edge Heat Transfer Tests

Objective

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

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

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

Progress for this Quarter

A new tip turn internal cooling circuit configuration was identified. The existing liquid crystal model is being retrofitted to this new configuration, and tests will be completed early in 3Q99.

Detailed pressure measurements were made for the trailing edge region of the second-stage bucket. These measurements were submitted to the GEPS engineers and were used to adjust and validate the 1D flow models.

Plans for Next Quarter

Liquid crystal tests of the new tip-turn configuration will be completed in 3Q99.

Verification of detailed predictions of flow distribution in the trailing edge cavity of the second-stage bucket is almost complete. Some consulting related to the second-stage bucket internal cooling circuit remains to be done.

Technology Application

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

The results of this task will also be used to validate design predictions of internal cooling flow distributions and heat transfer for the trailing edge region of the second-stage bucket.

Section 2.2.3.5.8 (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.

The objective of the task is to build a representative model of the trailing edge cavity and measure the local heat transfer coefficients to ensure that (1) the heat transfer coefficient correlations used in the design are appropriate, (2) there are no flow recirculation or uneven distribution regions where the heat transfer coefficients are lower than the expected values, and (3) to measure friction factors and heat transfer coefficient for the low-aspect-ratio/high-blockage trailing edge turbulated holes.

Progress for this Quarter

Activity has not been initiated. The team is waiting for design concepts to be determined.

Plans for Next Quarter

Plans will be formed once design concepts are defined.

Technology Application

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

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

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

Pending the completion of improved regional designs and associated design optimization studies, no activity took place in 2Q99 to extend this effort to revised geometries.

Plans for Next Quarter

When Design Engineering completes their evaluation of improved or redesigned regions, one or more models will be designed and fabricated for validation testing. Model tests will then be performed. Validation and optimization tests similar to those performed on the fillet regions of the first-stage nozzle may also be conducted on other internally cooled features of the nozzle design.

Technology Application

The first-stage nozzle endwall edge regions represent the furthest extent of impingement cooling within the steam circuit of the nozzle. These edge regions must balance the local cooling requirements with those of more inboard regions that experience cross-flow effects from the edge flow. The other fillet regions of the nozzle represent areas of casting orientation changes, TBC structural variations, in-plane thermal gradients, and stress concentrations and, therefore, require more detailed knowledge of the local heat transfer conditions.

The liquid crystal test models will provide detailed heat transfer coefficient distributions for specific geometries of the endwalls such as those mentioned in the preceding paragraph. These data will be used to confirm design and component lifing. The models will provide vehicles to further optimize this cooling as required.

Section 2.2.3.8 (GTETSP) STEAM PARTICULATE DEPOSITION

Section 2.2.3.8.1 (GTETSP) Steam Cooling System Cleanliness

Objective

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

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

Progress for this Quarter

Surface Cleanliness Measurement

A new surface cleanliness test involving the measurement of reflectivities of cloth smears was developed and transitioned to the Greenville factory floor. Standard commercial cloth smears are mounted on special tools and used to collect contamination within masked areas on a surface following specified, but simple, procedures. The reduction in reflectivity of the smears is then related to the amount of sampled contamination by previous calibration. Calibrations and gauge R&R tests were conducted using two types of contamination found in the factory. The sampling and measurement equipment was mounted on a rolling 2 foot × 2 foot rack in Greenville, and it is now being used to establish cleanliness levels in the plant. Because the new measurement process is quick, and easy to understand, it provides an archive record of the contamination on the labeled swatch. The measurement was disclosed for possible patent application.

No additional work was done on this task in 2Q99 other than the measurement being used by Greenville production staff.

Coolant System Flush

An apparatus design was completed in 1Q99 containing a first- and second-stage bucket pair, with cross-tube, rotor manifold-, axial tube, and radial tube components to determine flush feasibility. In 2Q99, the apparatus was under construction at the supplier.

In 2Q99, continuing consultations were held with GEPS staff on the analysis of possible failure modes of the filtration system, and final specification of instrumentation and equipment to monitor their status.

Plans for Next Quarter

Consultation will continue on application of the cleanliness measurement system on the Greenville floor as requested. Assembly and qualification of the surface cleanliness measurement equipment at Houston will be overseen. The flush rig assembly at the supplier will be reviewed before shipment to Greenville. Guidance will be provided on the filing of patents on earlier disclosures of concepts for detecting steam leaks in operating H-machines by conducting dosing- and exhaust- measurements.

Technology Application

Output of this task has contributed to the identification, experimental validation, and specifications for the on-line particulate filter system for steam ordered from the vendor for the first plant. The surface cleanliness measurement that was developed was quickly transitioned to the factory floor where it is now in use. Successful demonstration of an ability to flush the cooling system components will not only improve system startup reliability, but also ensure that contamination will not limit time between outages for engine disassembly.

Successful demonstration of an exhaust-based steam leak sensor could provide a lower-cost backup to the mass-balance computational system specified for the first installations.

Section 2.2.4 (GTMT) MATERIALS TECHNOLOGIES

Section 2.2.4.1 (GTMTSE) Steam Effects on Mechanical Properties

Objective

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

Progress for this Quarter

The creep testing in steam for Ingot 4 material concluded with 6,424 hours. Another test was started in steam. High Cycle Fatigue (HCF) tests of the same material in steam were concluded. A draft report was written for Design Engineering. Low Cycle Fatigue (LCF) testing of this material was resumed using the improved calibration method.

To rationalize the influence of a steam environment and grain size on LCF behavior and crack growth rates, standard LCF and crack growth specimens were machined from coarse grain slabs and fine grain slabs, and flat specimens were machined from a cast manifold. LCF tests were conducted at two temperatures in air and steam. Crack growth tests were performed in air and steam, and specimens were made from slabs with different processing parameters. Part of the LCF tests and all of the crack growth tests on fine grain slab material were completed. Half of the crack growth tests on cast manifold material were completed. Tensile tests were completed on coarse grain and fine grain slab specimens, and flat specimens machined from cast manifolds at a range of temperatures from 68F to 1100F.

Additional second stage nozzle material test specimens were delivered to the test laboratory. This delivery included ten compact tension specimens.

Plans for Next Quarter

The creep and LCF testing of rotor material will continue. Additional LCF tests on coarse grain cast slab material are planned after the fine grain slabs and cast manifold specimens are finished. Additional tensile and LCF specimens will be machined from 718 welds. Tensile tests will be done at four temperatures. One stress rupture test will be conducted. Tensile, LCF and crack growth tests are planned on welded specimens representative of the steam delivery system. No additional testing of hot gas path materials in steam is planned.

Technology Application

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

Section 2.2.4.6 (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

Visited compressor discharge diffuser supplier. Approved First Piece Qualification (FPQ) documentation and castings.

Plans for Next Quarter

No future work planned for this activity.

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

Three sub-scale forgings were made from ingot material that was purposely melted with the intent of producing internal defects. These forgings, along with the Stage 3 turbine wheel from an earlier test rotor and a supplier's prototype forging will be used to establish the capability of the phased array to distinguish the various types of defects. Subsequent metallography of the samples confirmed the results. Twenty-five samples are planned to be taken from the above material for additional tests.

A larger diameter IN718 ingot was melted to test conditions to promote the presence of microstructural conditions of interest. Forging of the ingot was completed and the part was sent for ultrasonic evaluation. The Ultrasonic Test (UT) evaluation of these pancake forgings is in progress. UT of the first forging from a second supplier showed excellent results. UT of the first forging from a third supplier showed poor results. Indications in the third supplier forging will be trepanned and evaluated for causes of these indications.

Additional hold time Low Cycle Fatigue (LCF) tests, in air, of Ingot 4 material continued. One specimen has exceeded 5,853 cycles. A radially oriented specimen is running with 768 cycles as of this report. Fourteen of the fifteen planned tests for Ingot 3 material, the FPQ forging , were completed. The longest tests are now at about 29,000 hours. Thirteen of the fifteen planned tests of Ingot 4 material were completed. Of the two tests in progress during this reporting period, the longest test is now at about 19,000 hours. A final report was received from the laboratory performing static crack growth rate testing. The results of High Cycle Fatigue (HCF) tests of one particular test regime were completed and are under review.

Plans for Next Quarter

Testing of the three "seeded" forgings and identify indications for application of the phased array will be completed. Trepans will be removed later this year for LCF testing and metallographic evaluation. UT evaluation of the third supplier forging and subsequent cut-up for detailed analysis will continue. Creep rupture tests will continue. Hold time LCF tests of

Ingot 4 material will continue. Hold time crack growth tests will begin. First and second heat data for IN718 will be reviewed and new/revised handbook curves will be issued.

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

A part specification for the manifold was issued. A grain size study of this component was completed that highlighted the preferred size range, balancing properties against process optimization. A weld repair procedure and qualification of the supplier were completed. Participated in a concept review/supplier selection discussion with Design Engineering. The supply and return elbow First Piece Qualification (FPQ) packages were reviewed. Relaxation behavior of IN718 was reviewed with three different heat treatments as part of the alternate spoolie material program.

Two different heat treatments were applied to the alternative spoolie material to obtain coarse and fine grain microstructures. Five specimens each were machined from the two different batches of material. Ten specimens were machined from the current spoolie material to provide baseline data. Stress relaxation tests were performed at two temperatures and at two strain ranges with the current spoolie material. After the resulting data were reviewed it was decided to abandon the alternative spoolie material program.

Plans for Next Quarter

The stator steam manifold part specification will be revised. Non Destructive Test results for the manifold will be reviewed when submitted by the supplier. A new part specification will be written for the bore tube. Analysis of the rig tested spoolies will be completed.

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

Progress for this Quarter

Long term creep tests on various hot gas path materials were continued. The total hours accumulated on creep specimens are as follows: first stage airfoil material – 19,909 hours, second stage bucket material – 25,930 hours and third stage nozzle material – 16,649 hours. Test specimens were machined from cast slabs of the third and fourth stage bucket material. These included specimens for dynamic modulus, creep, tensile, and High Cycle Fatigue (HCF).

Plans for Next Quarter

Conduct dynamic modulus and various mechanical tests on the third and fourth stage bucket material.

Technology Application

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

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 the braze and weld repair processes for first and second stage airfoil materials was continued. Screening tests of the first stage nozzle cover joint were completed, and two processes for additional evaluation were selected. Screening tests for the stage two nozzle cover joint were completed. The stage one bucket tip cap joint tests were completed, and a report to Design Engineering was issued. First and second stage bucket root cover plate tests were completed. The stage 1 nozzle end cover base metal tests were completed to help evaluate the resulting joint behavior.

Plans for Next Quarter

Studies will continue to evaluate and enhance repair methods for hot gas path materials with selection of a process and subsequent optimization of parameters. The first and second stage nozzle tests to evaluate four joining processes will be completed. Testing of first and second stage bucket tests to evaluate six joining processes will be completed. Testing of first stage shroud, first stage bucket shoulder and first stage bucket trailing edge joints will be initiated. Defect correlation will be continued.

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

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

The TBC Process and Diagnostics portion of the task will focus on achieving a better fundamental understanding of the TBC application process. Specific process conditions critical to the thickness and properties of the TBC system will be evaluated. Continuing work will focus 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 which most strongly influence process variability and TBC quality.

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

Progress for this Quarter

Robotic Motion Control and Programming Methods for ATS Airfoils

Eleven FANUC Robotics M710i/RJ2 systems have been installed, with plans for an additional 13 installations by 2001. This will bring the total number of GE spray cells capable of coating ATS airfoils to 24, located worldwide. As part of this initiative, standards for thermal spray and advanced robotics systems are being established; including installation, calibration, and programming; to assure that process transfer among the different cells can be readily accomplished.

Robot alignment and calibration time was reduced by a factor of four using the new DynaCal™ System. A method to correct the robot paths for the effects of variation in true part position due part-to-part dimensional variation and fixture alignment variation has been developed and demonstrated via computer simulations. A laser triangulation technique using three spatially offset laser measurements is being developed to simultaneously measure gun/part velocity, standoff and angle.

An off-line simulation tool to predict variation in TBC thickness and microstructure on ATS airfoils is being developed. The thickness predictor model integrates part geometry, robot motions, and spray pattern "footprint," in order to predict the TBC thickness distribution over the entire part surface. The asymmetric spray pattern footprint has been successfully characterized on a flat plate using an inverse analysis technique. The model was exercised using the bucket replica geometry, the "taught" robot motion path, and a representative spray footprint. Agreement between the predicted and actual thickness distributions was improved when measured gun/part velocity and standoff data were used in place of "taught" path data.

Coating Processes for ATS Components

A) Nozzles

Coating and hand surface finishing of the first set of ATS stage two nozzles were completed. Over 230 locations on each nozzle were inspected using automated CMM to evaluate TBC process capability. Qualification of the coating and hand surface finishing processes for the ATS stage one nozzles was completed.

B) Buckets

Coating and hand surface finishing of the first sets of ATS stage one and stage two buckets were completed.

C) Shrouds

Coating and CNC surface finishing of the first set of ATS stage two shrouds were completed. Qualification of the coating and CNC surface finishing processes for the ATS stage one shrouds was completed.

D) Transition Pieces

Coating of the first set of ATS transition pieces was completed.

<u>Bond Coat Processes</u>

<u>Note</u>: *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.*

A) Thermal spray bond coats

NiCrAlY bond coats applied by Air Plasma Spray (APS) provide excellent TBC thermal cycling performance, and are used on the first production ATS gas turbine airfoils and transition pieces. However, this bond coat is relatively porous and, therefore, not sufficiently protective to meet full ATS component life requirements for some substrate alloys. As a result, a variety of bond coat compositions and processing techniques have been evaluated.

Candidate dense, protective thermally sprayed bond coats for ATS gas turbine airfoils and shrouds were identified. Specifications were written for single layer bond coats applied by Vacuum Plasma Spray (VPS) and High Velocity Oxy-Fuel (HVOF) processes. Two-layer bond coats and alternate bond coat chemistries are being evaluated using furnace cycling and oxidation burner rig exposure testing.

B) Brazed bond coats

Braze coating processes may be needed to meet ATS life requirements on certain components where spray gun access is restricted. These components include the transition piece and stage two nozzle weld joint. The as-sprayed APS bond coats are not sufficiently protective to certain substrate alloys, particularly GTD222. Two types of braze-APS coatings were 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.

An optimized Type 2 coating was selected for first use on combustor components. Evaluations are in progress to determine the extent of elemental interdiffusion between the bond coat and substrate, and the effect of the bond coat upon the mechanical properties of the substrate.

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.*

TBC protective coatings were developed to extend turbine service conditions beyond those currently allowable by improving resistance to deposits of Calcium-Magnesium-Aluminum-Silicate (CMAS). An optimized multi-layer coating system deposited by Chemical Vapor Deposition (CVD) was developed. Long-term durability testing (1000 hot hours) is being performed using the JETS thermal gradient test rig. Hot erosion testing will be performed using the BECON test rig at GE Aircraft Engines. A pilot CVD coating reactor is being set up at GE CR&D to coat ATS nozzles for cascade testing.

TBC Manufacturing Technologies:

Production coating of the first ATS components is being conducted at three GE sites in order to level load available spray facilities. GE resources from several sites have teamed to carryout this critical initiative. Procedures for each component are being established; which include Manufacturing Process Plans (MPPs), Operations Methods, Quality Data Collection (QDC), Non-Destructive Testing (NDT) operations, and Final Audit. Local TBC repair procedures were developed and qualified for production parts

Processes for pre- and post-coat preparation and cleaning, bond coat and top coat deposition, top coat surface finishing, coating inspections, and heat treatment have been qualified on the ATS stage two nozzle, stage one bucket, stage two bucket, stage two shroud, and transition piece.

A) Surface finishing methods

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

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). CNC Grinding is the most promising approach when the as-sprayed coating thickness distribution is determined using eddy current measurements in combination with CMM measurements. GE-developed software for integrating these data was provided to a grinding vendor. A study is being conducted to reduce the number of setups required for grinding 100% of the coated surface.

The development plans consist of three parts. Part #1 involves a CAD Simulation Study of four ATS gas turbine components to define the work envelope, fixturing, and tooling requirements in order to optimize grinding process efficiency. Part #2 involves qualifying the on-line EC measurement system and demonstration of process capability on ATS buckets and nozzles. Part #3 involves final qualification of the TBC grinding process on all ATS airfoils.

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 will be used for the first ATS buckets as well. A second alternative finishing technique that utilizes part-specific soft tooling and conformable abrasive media demonstrated promising results on flat samples and on the suction side of a bucket. Soft tooling is being fabricated to allow sequential finishing of the pressure and suction sides of the bucket.

B) Stage two nozzle doublet joint

Air plasma spray processes for applying bond coat and top coat to the welded joint of the stage two nozzle doublets were developed using a mini-gun. Masking and spray motions have been developed, and process qualification is nearly complete.

C) Instrumentation

Techniques for applying TBC over strain gages and embedded thermocouples were evaluated and transitioned to manufacturing.

D) Cooling Holes

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

<u>TBC Process and Diagnostics</u>:

Plasma guns that operate at longer standoff distances and higher powder injection rates are desired for manufacturing. The TAFA Plazjet gun was selected for the next generation TBC process. This gun has the capability of achieving similar or better TBC properties than the Metco 7MB gun at much longer standoff distances and over 3X higher powder injection rates. Plazjet guns will be installed at three GE sites in 1999, to be used for both production and development.

Qualification experiments using the TAFA Plazjet were completed at GE CR&D. Development of acceptable coating deposits was greatly accelerated through leveraging of process diagnostics developed in a recently concluded ATP program. Excellent coating properties were achieved at a significantly higher powder injection rate, reducing process cycle time by over 2X.

A comprehensive TBC process/properties database is being accumulated, including tensile, modulus, deposition rate, thermal conductivity, surface roughness, and furnace cycle life. Regression models to predict TBC properties, including both mean and standard deviation, from the controlling process parameters will be developed. This is being done as part of the GE "Design for Six Sigma" (DFSS) initiative.

Non-destructive TBC Thickness Measurement:

An automated ceramic coating thickness measurement system consisting of a flexible eddy current probe in combination with a multi-axis contact probe scanner was developed. The flexible eddy current probes are manufactured by GE Reuter Stokes. Installed Coordinate Measuring Machines (CMMs) are used as the scanning devices. Several hundred inspection points can be measured in under fifteen minutes, which reduces inspection time by over 5X compared to manual measurements. The development CMM system will be upgraded to allow both on-line and off-line programming via a new PC-DMIS system.

An improved flexible eddy current probe configuration is being developed, both to reduce the probe cost and to improve the probe durability. Baseline data on probe life was obtained. Equipment for life testing the current and new probe designs was received and will be operational in 3Q99.

Non-destructive TBC Microstructure Evaluation:

Laser Ultrasound (LUT) is being developed for non-destructive evaluation (NDE) of TBC microstructures. Current techniques utilize mechanical resonance to extract the coating modulus indirectly. The LUT 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.

Young's modulus and tensile properties are extracted from the measured signal; these data have been validated by destructive measurements on coupons. The ATS Cascade Nozzles are being extensively evaluated to further validate and refine these correlations. Good correlations were observed between LUT tensile predictions and destructive pull-tests. However, some of the microstructural variation present in the ATS Cascade Nozzles resulted in loss of signal due to attenuation, as well as a different transfer function from that obtained on the coupons.

A series of experiments on thermomechanical fatigue (TMF) specimens was begun, in collaboration with the TBC Design Data and Life Analyses task. Although these specimens were prepared to be nominally identical, the LUT data identified differences in microstructure and mechanical properties, with the eight specimens falling into two broad categories. LUT data will also be acquired on a set of porous TBCs, to support additional process development for application to long-life combustors.

Quality Function Deployments (QFDs) were performed with engineering, manufacturing and services to define the functional requirements for the LUT system. Cost reduction of the instrumentation was very important. A low cost Sagnac interferometer developed jointly by Northwestern University and GE CR&D meets all initial requirements. The prototype instrument will be delivered to GE CR&D in 3Q99. A competing technology, using a photorefractive interferometer, meets performance targets at greater standoff distance, but at higher cost. Based on the output of the QFDs, the Sagnac interferometer will be developed as a first generation system for both manufacturing and field inspection applications, while the photorefractive technology will be developed as a second generation system for manufacturing, where long standoff is desired.

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

Plans for Next Quarter

Robotic Motion Control

The new part calibration procedure on the ATS bucket replica and production parts will be demonstrated.

Thickness predictions on the ATS bucket replica will be improved by using measured gun/part velocity and orientation data in place of "taught" path data. The effects of particle "glancing" and "rebounding" on the spray footprint for different simulated geometries will be evaluated.

Part Coating Trials

Coating processes on production ATS stage one nozzles and shrouds will be qualified.

TBC Manufacturing Technologies:

The process for coating the stage two nozzle weld joint will be qualified.

TBC Process and Diagnostics:

Development of regression equations that relate TBC properties to process parameters using the TAFA Plazjet gun will be initiated.

Non-destructive TBC Evaluation:

The control software will be combined with LabView for data acquisition during the flexible EC probe life tests. Prototypes of several long-life probe concepts will be constructed.

Regression equations that relate destructive data from bucket samples to LUT measurements will be tested. Pass/reject criteria for inspection will be developed.

The prototype shop instrumentation at GE CR&D will be demonstrated.

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 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 differing 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

Funding for this activity has been discontinued.

Cascade Nozzle Evaluations

Destructive and non-destructive evaluations are being performed on four nozzles: two nozzles from the low cycle fatigue (LCF) test, one remaining nozzle from the heat transfer test and one nozzle that was not tested. All of these nozzles were coated in an identical manner.

Approximately 80 specimens were removed from each of the four nozzles using waterjet cutting. Samples were taken from the leading edge and the concave and convex sides of the airfoil, and from both sidewalls (including fillets). Laser ultrasound (LUT) measurements were taken at each specimen location before the nozzles were sectioned. The untested nozzle was scanned non-destructively using both LUT and IR thermal imaging. Microstructural evaluations and tensile strength measurements are complete for the four nozzles. Other mechanical tests are in-progress.

A) Heat transfer test nozzles

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 locations close to those 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 the Nozzle #30, implying that the same damage mechanism occurred in both tests.

Plans for Next Quarter

Evaluations of mechanical properties will be completed on coupons removed from the ATS Cascade Nozzles. Transfer functions between microstructural variables and laser ultrasound parameters and between microstructural parameters and thermal conductivity will be developed.

Technology Application

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

Section 2.2.5.3 (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. 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 thermal-mechanical fatigue, compression shear, tensile, ballistic impact, and hardness tests. Thermal-Mechanical Fatigue (TMF) data will be used with Furnace Cycle Test (FCT) data to predict or estimate TBC life. Other data will be used to rank TBC based on empirical parameters.

Coating of test specimens comprising eight different substrate / bond coat / top coat systems has begun. Specimens were machined from Rene N5, GTD111, GTD222 and Hastelloy-X alloys. Two types of specimen were prepared: 1.00 diameter x 0.125 inch thick buttons and 7 inch long x 0.250 inch thick TMF bars. All GTD111 and GTD222 specimens were overaluminided using a NiAl coating to protect the substrate metal from oxidation during high temperature testing. One of the TBC systems is a duplication of the TBC applied to the ATS Cascade Nozzles. This TBC was deposited using certain process conditions which deviated from standard practice, and may have contributed to the early TBC spallation observed on some nozzles.

TMF and FCT testing is in-progress on single crystal N5 substrate coated with APS NiCrAlY bond coat and APS DVC topcoat. Additional samples are being thermally aged in order to study the influence of exposure on the TBC properties and impact behavior.

<u>Furnace Cycle Testing</u>

Conventional ("porous") and advanced ("dense vertically cracked" or "DVC") TBC specimens were furnace cycled at 1148°C (2100°F) and 1093°C (2000°F) using dwell times of 0.1, 0.75, 10, and 20 hours per cycle. The majority of specimens were cycled to failure, although some specimens were removed at intermediate times for tensile adhesion testing and laser ultrasound measurements. A small number of specimens were intentionally exposed to two different dwell times in order to test the influence of thermal history on remaining TBC life.

Furnace cycle testing at 1037°C (1900°F) was begun for the two TBC systems, using dwell times of 0.1, 0.75, and 10 hours per cycle. These furnace cycle tests are projected to be completed by 4Q99, although the 10 hour cycle tests may not be completed until 2000. To date, 18700, 8180 and 792 cycles have accumulated on these samples, respectively. Some specimens are being removed at intermediate times for tensile testing and microstructural analysis.

The Rene N5/APS GT21/DVC TBC data were fit using the cumulative damage model for the cases of parabolic and cyclic oxidation. In both cases a reasonable fit was obtained to the FCT data; however, the two curve fits yield markedly different estimates for the TBC spallation lives at low temperatures. Examination of the oxide growth kinetics at 1093°C (2000°F) indicated that a two-stage parabolic oxidation damage model is appropriate for this TBC system.

Thermal-Mechanical Fatigue Testing

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

Trial TMF tests revealed that the initial test specimen geometry was susceptible to buckling under compressive loading. A new gripping method was developed, which eliminated buckling for compression strain ranges up to -0.5%. A new GE Specification was prepared for TMF testing.

An in-phase TMF test on a single crystal N5 substrate coated with APS NiCrAlY bond coat and APS DVC top coat is in-progress. 500 cycles have been accumulated on this specimen without TBC failure. The quality of the TBC applied to the TMF samples is being assessed via non-destructive evaluations (NDE) prior to and following testing. Laser Ultrasound (LUT) and Infrared thermal imaging (TIR) techniques have been selected for this purpose.

Thermal Conductivity

Prioritization of 1999 activities occurred. The highest priority tasks are: 1) determine the gas pressure dependence of thermal conductivity, 2) determine thermal conductivity of TBC following field service, and 3) better quantify the spatial variability of thermal conductivity using the ATS Cascade Nozzles. Some work is also intended to be done in sample preparation and measurement methods for bond coat samples, pending definition of spray parameters and sample availability.

A) Planar samples

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

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

B) Curved samples from parts

Evaluation of sections from ATS Cascade Nozzles and field returned parts is being performed. Systematic variation in thermal conductivity was observed on the ATS Cascade Nozzles according to location. The source of this variation is the TBC microstructure, which is strongly dependent upon the spray gun motions and local part temperature. Fillet samples could not be prepared previously due to TBC spallation during waterjet sectioning. Improved waterjet conditions have been found by sectioning the nozzle first into smaller parts (allowing better fixturing, and consequent better waterjet placement), resulting in a higher yield of fillet samples. Free-standing TBC samples were prepared from shrouds and buckets tested in commercial gas turbines for up to 24,000 hours.

C) Bond Coat samples

Measurements performed in 1998 showed that the bond coat contributes about 10% of the thermal resistance of the TBC/bond coat system. This is considered to be significant, so further bond coat measurements are needed. Techniques for bond coat sample preparation are being developed.

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

Continue testing at 1038°C (1900°F).

Refine the cumulative damage model using the new oxidation kinetics.

Thermal-Mechanical Fatigue Testing

Continue testing coated samples. Evaluate spalled samples using LUT and TIR.

Evaluate a new specimen which will permit testing at strain ranges above -0.5%.

Thermal Conductivity

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

Prepare samples for evaluation of the effect of TBC thickness on thermal conductivity.

Technology Application

The results of this task are used to update the design databases. In addition, a database will be established which will link TBC properties and durability in laboratory tests to TBC durability in the ATS 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 which result in improved properties and durability.

Section 2.3 (CC) COMBINED CYCLE INTEGRATION

Section 2.3.1 (CCUA) Unit Accessories

Objective

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

Progress for this Quarter

Cooling Air Cooling System

In the second quarter an extensive design review was undertaken to determine how to further increase the reliability of the Cooling Air Cooling System. This involved weekly meetings with Design Engineering, Systems Engineering and the Reliability group to decide what steps should be taken to improve the system's reliability for the 7H machine.

It was decided to undertake several changes to the 7H design, including a change in the type of heat exchanger used, and further changes to increase the system's overall flexibility. These changes will not only ensure a more robust design, but also greater operating variability, both vital attributes when introducing a new product.

Fabrication of the 9H skid continued on schedule. No major difficulties developed.

Steam Cooling System

After extensive collaboration with other GE departments during the second quarter, the data blocks, information required to complete the design of the 9H steam valves, were completed. This information will allow design work to continue to completion. While the data blocks were being completed, the design process was furthered by using estimates of design criteria while waiting for specific values to be finalized. By using this procedure, only the final steps of the detail design remain. This proactive approach will ensure scheduling demands are met.

Design work was completed on the 9H steam filter.

Clearance Control System

In the second quarter, efforts were focused on ensuring proper installation of the additional piping filtration improvements that had been decided upon in the first quarter. This installation also required the writing of a test plan for the testing procedure that will be performed during the 9H FSFL pre-shipment test, later this year. The test plan will require extensive work with Gas Turbine Design Engineering, Accessory Design Engineering, and the Test Stand personnel.

Exhaust Diffuser

The main efforts on the 9H exhaust diffuser were spent resolving an issue arising from one of GE's customers concerning alterations of the customer's plant and eliminating any potential performance impacts. This issue is still ongoing.

Discussions continued with GE's technical partners in order to determine the most efficient manner to achieve the manufacture of the exhaust diffuser. These discussions will continue into the next quarter and represent a key issue in the implementation of this project.

The fabrication of the 9H diffuser is continuing on schedule and is due for completion in the third quarter.

Plans for Next Quarter

For the accessory systems being designed for the advanced gas turbine, the following work is planned during the next reporting period.

Cooling Air Cooling System

The Cooling Air Cooling skid fabrication will be completed. This will represent a major milestone in the design process. Any possible alterations will then be evaluated.

The design process on the 7H system will continue to the detail design stage. This will require complex combined cycle performance requirements, as well as meeting System performance and reliability demands.

Steam Cooling System

The third quarter's efforts will be to complete the detail design of the steam valves. Because of the long cycle time needed to procure these valves, design work will involve close communication with the valve suppliers to ensure the timely shipment of hardware. It is possible that further changes to design requirements could result from testing planned for later this year, and this possibility will be considered when performing design work.

Clearance Control System

In the third quarter, the installation of the filtration upgrades will be completed. The modifications will require testing to ensure their correct selection and installation, and the writing of a test procedure will be the focus of the third quarter's efforts. This process will require interfacing with several stakeholders within GE to ensure that the plan will produce the data needed by different departments, and meet the rigorous requirements set to ensure the filtration is effective.

Exhaust System

Discussions with our customer will continue to resolve issues with piping and performance concerns. Responding to these concerns involve working with other departments and our supplier and will be an ongoing process. Discussions with GE's technical partners also represent a key issue and will continue in the third quarter. The fabrication of the system is due to be completed in the third quarter.

Technology Application

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

Section 2.3.2 (CCCL) Controls

Objective

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

Progress for this Quarter

The study of control loop dynamics using a simulation program continued, extending to full combined cycle operations. Control algorithms for the gas turbine and steam turbine were coded into control system programs to support the first combined cycle application, with the focus on steam cooling control strategies. In addition, engineering validation of the software continued, using a simulation environment. Efforts were continued to implement hardware and software modifications necessary to support the 9H FSFL pre-shipment test. Field testing of the triple-redundant control system continued. Field data collection process continued to be tested to verify operational reliability.

Plans for Next Quarter

Study of control loop dynamics will continue, with focus on combined cycle operability. Continue to develop control and protection algorithms for the steam cooling system and coordination with the steam cycle operation. Continue to develop platform to verify control programs and operational sequences using actual control panels in a fully combined cycle test environment. Finalize control preparations to support second full speed testing.

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 assessment of the cooled cooling air system was completed. The reliability assessments of the steam cooling system, fuel gas heating system, aft wheel space cooling system, rotor steam delivery circuit, lube oil system, and several other smaller systems continued.

Reliability block diagrams for the gas turbine flange-to-flange, which includes scheduled maintenance intervals to replace/refurbish components, were constructed.

A spoolie reliability and lifing assessment was performed, based on test results obtained at GE CR&D. This information will be utilized during the reliability assessment of the rotor steam delivery circuit.

Plans for Next Quarter

The steam cooling system assessment will continue, including rotor steam delivery reliability assessment, stator steam cooling circuit, and the overall steam cooling system.

Reliability modeling of the gas turbine flange-to-flange systems (compressor, combustion, turbine, and structures) will continue in order to evaluate the estimated reliability and availability versus the overall plant goals. This will also include an assessment of the required scheduled maintenance.

Reliability assessments will continue for several key systems, including aft wheel shaft cooling system, lube oil system, hydraulic system, and others.

Technology Application

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

Section 2.3.4 (CCSD) Combined Cycle Systems Design

Objective

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

Progress for this Quarter

Cooling steam schedules were developed for use during transfer from the air cooled to steam cooled operating modes which satisfy both gas turbine and steam turbine startup requirements within the constraints of steam production and startup time budgets. Steady state models were developed for operation with the gas turbine on air cooling, and with cooling steam supply from the HRSG, to support detail piping design and stress analysis for the launch S109H plant. An evaluation was completed to establish the optimal means of supplying the 2nd stage nozzle with its required cooling air on the S107H. Development of the thermal dynamic model (TDM) on a new platform has been completed. Testing of the model and controls logic has been performed in the course of executing startup and shutdown runs. A preliminary cold start run from turning gear to full load conditions has been successfully simulated, followed by a normal shutdown. A hot start simulation is in progress.

Plans for Next Quarter

Optimization studies for the combined cycle sub-systems will continue. Improvements and extensions to the performance model will continue to enable automation of design point calculations. Hot and warm start simulations will be completed using the TDM. Following that, system operability limits, especially as response to load change demands or grid upsets, will be investigated in more detail. A complete suite of startup and shutdown runs will be completed, including hot, normal and cold day ambient effects.

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

During 2Q99, the IN 718 turbine rotor forgings for the first 7H turbine rotor completed sonic inspection and machining was begun. All 9H FSFL pre-shipment components were assembled in the steam cooled rotor, which is in the 9H gas turbine at the test stand.

Modifications to Test Stand #8 were completed, and the 9H gas turbine was moved to the test stand. Design of modifications to the test stand for 7H testing were mostly complete and the procurement process was initiated.

A detailed Engineering and Manufacturing schedule for the 7H first unit assembly and FSNL test was developed in 1998 and is being used to monitor the component and unit assembly schedules.

Plans for Next Quarter

During the next reporting period the 9H steam cooled Turbine Rotor will be tested as part of the 9H gas turbine FSFL pre-shipment test. The 7H Turbine Rotor forgings will finish machining and be assembled into a 7H Turbine Rotor. Test stand modifications required for the 7H gas turbine FSNL test will be started.

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

The IGCC Task will be initiated.

Section 2.7 (PM) Program Management

Objective

Within GE Power Systems (GEPS) Engineering, an ATS Program Office will be established and a Program Manager and a Contract Administrator will be assigned. The Program

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

Actual scope, schedule, and budget will be tracked against plan. An integrated program plan will be maintained, including a detailed Work Breakdown Structure, 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 Agreement's Financial Assistance Reporting Requirements Checklist will be supplied. Technical papers will be submitted for presentation to professional society meetings. Open communications will be maintained with DOE and the Industry Advisory Board.

Progress for this Quarter

A Program Review was held at GEAE in Evendale, OH to review the 7H compressor rig test plan and hardware assembly before being shipped to the Lynn, MA test facility.

Plans for Next Quarter

A Program Review will be held in Schenectady, NY to witness the turbine rotor tests being performed in the Gas Turbine Development Lab.

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

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

Section 2.1 (NE) NEPA

Objective

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

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

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

Plans

This task was completed in 4Q97.

Technology Application

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

Section 2.2.1 (GTAD) Aerodynamic Design

Objective

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

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.2.3.1 (GTFFTR) Turbine Rotor Mechanical Analysis

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

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

Section 2.2.2.3.2 (GTFFTR) Wheel Forging Residual Stress Analysis

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

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

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

Objective

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

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

Plans

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

Technology Application

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

Section 2.2.2.4.1 (GTFFTB) S1B and S2B Wheel Dovetail Analysis

Objective

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

Plans

This task was completed in 2Q97.

Technology Application

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

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

Objective

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

Plans

This task was completed in 3Q97.

Technology Application

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

Section 2.2.2.4.3 (GTFFTB) Bucket Wide Grain Sensitivity Analysis

Objective

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

Plans

This task was completed in 1Q97.

Technology Application

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

Section 2.2.2.4.3.1 (GTFFTB) Bucket Robust Design and Life Assessment

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

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

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

Objective

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

Plans

This task was completed in 2Q97.

Technology Application

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

Section 2.2.2.4.6 (GTETEH) S1B External Heat Transfer

Objective

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

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

Plans

This task was completed in 3Q98.

Technology Application

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

Section 2.2.2.4.8 (GTETIH) S1B Leading Edge Turbulator Tests

Objective

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

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

Plans

This task was completed in 4Q98.

Technology Application

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

Section 2.2.2.5.1 (GTFFTS) Turbine Stator Robust Design

Objective

The objective of this work was to develop and apply robust design methods for the development of steam-cooled components of the advanced gas turbine. The goal of this effort was to achieve high standards of performance, quality, and reliability for these components by performing the following tasks during the product development cycle: (1) apply, and develop as needed, the robust design methodology to first- and second-stage nozzles; (2) apply the robust design methodology to some of the steam- and air-cooled stator components (e.g., first-stage shroud and turbine inner shell); (3) provide consulting and support for applying the robust design methodology to some of the critical rotor components (e.g., manifold, steam tube bushings, and spoolie); (4) provide consulting and support for integration of design, manufacturing, and assembly; and (5) train the GEPS staff on the concepts, methods, and tools for achieving robust design.

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

Plans

This task was completed in 4Q97.

Technology Application

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

Section 2.2.2.6.1 (GTFFSTEF) Exhaust Diffuser Performance

Objective

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

The test program included the installation and test of a scale-model diffuser with flowpath geometries and components compatible with the ATS gas turbine. Specifically, the cost-saving idea of internal insulation required axial ribs in the walls of the diffuser flowpath. Impact on pressure recovery was measured. Several other tests were performed, each with the aim of maximizing performance. These tests included examining variations in flowpath, centerbody length and termination shape, steam pipe locations and fairings, and other diffuser features that affect performance. The final exhaust diffuser design was tested to verify that no acoustic resonances are excited, particularly at FSNL conditions.

Plans

This task was completed in 4Q97.

Technology Application

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

Section 2.2.2.6.2 (GTFFST) Steam Box CFD Analysis

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.2.7.1 (GTFFMS) Transient Gas Turbine Cycle Model

Objective

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

Plans

This task has been 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 2.2.3.1 (GTETNC) S1N DESIGN

Section 2.2.3.1.1 (GTETNC) Nozzle Cascade CFD Analysis

Objective

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

Plans

This task was completed in 1Q96.

Technology Application

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

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

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.3.4 (GTETRH) ROTATIONAL HEAT TRANSFER

Section 2.2.3.4.1 (GTETRH) Rotational Effects on Bucket Mixing Ribs

Objective

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

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

Plans

This task was completed in 1Q98.

Technology Application

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

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

Objective

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

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

Plans

This task was completed in 3Q96.

Technology Application

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

Section 2.2.3.4.3 (GTETRH) Rotating Trailing Edge Heat Transfer Tests

Objective

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

Plans

This task was completed in 4Q98.

Technology Application

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

Section 2.2.3.5.1 (GTETS2NHT) S2N Trailing Edge Flow Test

Objective

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

The model kept the important geometric variables of the passage close to the actual design. It had thin-foil heaters on both the suction and pressure sides, and liquid crystals to determine the temperature distributions. Tests were planned to investigate the triangular passage performance with several turbulator designs.

Plans

This task was completed in 3Q96.

Technology Application

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

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

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.3.5.4 (GTETIH) S1N Convex Cavity Heat Transfer Tests

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.3.5.5 (GTETIH) Bucket Tip Closed Circuit Cooling

Objective

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

Plans

This task was completed in 3Q96.

Technology Application

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

Section 2.2.3.5.6 (GTETLE) Bucket Leading Edge Heat Transfer Testing

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.3.5.7 (GTETIH) S1N Surface Enhanced Internal Heat Transfer

Objective

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

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

Plans

This task was completed in 4Q96.

Technology Application

The ANSYS analysis results provide the increases in wall temperature expected for various numbers of bumps missing. The acceptable temperature rise will determine the quality control criteria and the nondestructive testing technique for the missing bump number determination. The transient technique provides a nondestructive technique to check the non-uniformity of the cooling and the number of missing bumps.

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

Objective

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

Plans

This task was completed in 4Q96.

Technology Application

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

Section 2.2.3.5.10 (GTET) Impingement Degradation Effects -

Objective

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

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

Plans

This task was completed in 3Q97.

Technology Application

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

Section 2.2.3.5.11 (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. The first- and second-stage nozzles have several impingement-cooled flow cavities connected in series and in parallel depending on the design requirements. Design flow models involve several empirical friction factors and flow element head loss coefficients that were taken from the best knowledge available. The models need experimental verification with typical cast components.

The objective of the flow checks, conducted with air was to check the flowrates and static pressure distributions of typical cast first- and second-stage nozzle components. The results were compared with the design flow model predictions. The measured overall coolant flowrates for a given overall inlet-to-exit pressure ratio form the basis for future quality flow tests to ensure that every component fulfills the flow design requirements.

Plans for Next Quarter

This task was completed in 1Q99.

Technology Application

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

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

Objective

The effects of TBC surface roughness on external heat transfer were characterized using flat plates tested in an atmospheric wind tunnel. An advantage of flat plates over airfoils is that TBCs can be applied easily and polished to uniform thickness and surface finish. Full mapping of the TBC surface topography was performed to support infrared mapping of the surface temperatures (heat transfer coefficients). Reynolds numbers spanned those expected in the ATS turbine inlet nozzle surface away from the leading edge. Tests included plates with and without leading edge step heights to model the effects of component interface misalignments. Verification tests on airfoil replicas were also performed.

Plans

This task was completed in 4Q97.

Technology Application

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

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

Objective

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

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

Plans

This task was completed in 1Q97.

Technology Application

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

Section 2.2.3.6.2 (GTETEH) Surface Roughness Effects on Heat Transfer

Objective

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

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

Plans

This task was completed in 3Q96.

Technology Application

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

Section 2.2.3.7 (GTETCP) LCF COUPON TESTS

Section 2.2.3.7.1 (GTETCP) LCF and Crack Propagation Rate Tests

Objective

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

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

Plans

This task was completed in 3Q98.

Technology Application

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

Section 2.2.4.2 (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 were already 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 high cycle fatigue (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

The objective of this task was to gather information to support selection of materials for the variable guide vane (VGV) bushings and thrust washers in order 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 were evaluated.

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

Test results obtained from this task increased 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

The objective of this task was to develop improved gas path seals for the ATS turbine utilizing seal technology used in aircraft engine components where applicable. The technology was 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 was to develop and test hot gas path seals that meet both leakage performance and life requirements. Specifically, improved sealing performance that reduces the equivalent gap of the seal was sought by replacing the current Q-tip seals with a cloth sealing system. The cloth seals also need to meet the same full-life requirement.

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

Plans

This task was completed in 4Q97.

Technology Application

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

Section 2.2.4.14.2 (GTETBS) Steam Gland Brush Seals

Objective

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

Plans

This task was completed in 4Q97.

Technology Application

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

Section 2.2.4.11 (GTMTCB) Combustion Materials and Processes

Objective

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

Plans

No future work planned for this activity.

Technology Application

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

Section 2.5.3.1 (GTFFTB) Bucket TBC Roughness and Spall Characterization

Objective

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

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

Plans

This task was completed in 1Q97.

Technology Application

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

Section 2.6 (DE) Pre-Commercial Demonstration

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