#25

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GE Power Systems

Utility Advanced Turbine Systems (ATS) Technology Readiness Testing

PHASE 3R

Annual 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

STEM – shaped tube electrolyte machining

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

This report summarizes work accomplished from 4Q98 through 3Q99. The most significant accomplishments are listed below:

7H-Specific

- Continued design and manufacturing programs, utilizing information derived from the 9H component and full-scale testing programs.
- Completed 7H compressor rig testing at the GEAE-Lynn, MA test facility.
- Continued test cell preparation activities for the 7H FSNL test.

9H/7H-Common Technology

- Continued full-scale H-series combustor development at ATS design conditions.
- Installed the turbine rotor rig in the GEPS Engineering Development Lab test stand and initiated preparation for testing.
- Continued work with suppliers to develop single crystal casting technology for the large ATS gas turbine buckets and nozzles.
- Continued development of thermal barrier coatings (TBC) and demonstrated viable high speed, high accuracy TBC application robot control software for high deposition rate with uniform coverage.
- Continued development of nondestructive inspection techniques for single crystal airfoil production.

- Continued development of combined cycle system optimization analyses.

9H-Specific

- Completed the 9H FSNL test program, post-test hardware inspection, and test data analysis.
- Completed test stand modifications to meet 9H FSFL pre-shipment test requirements.

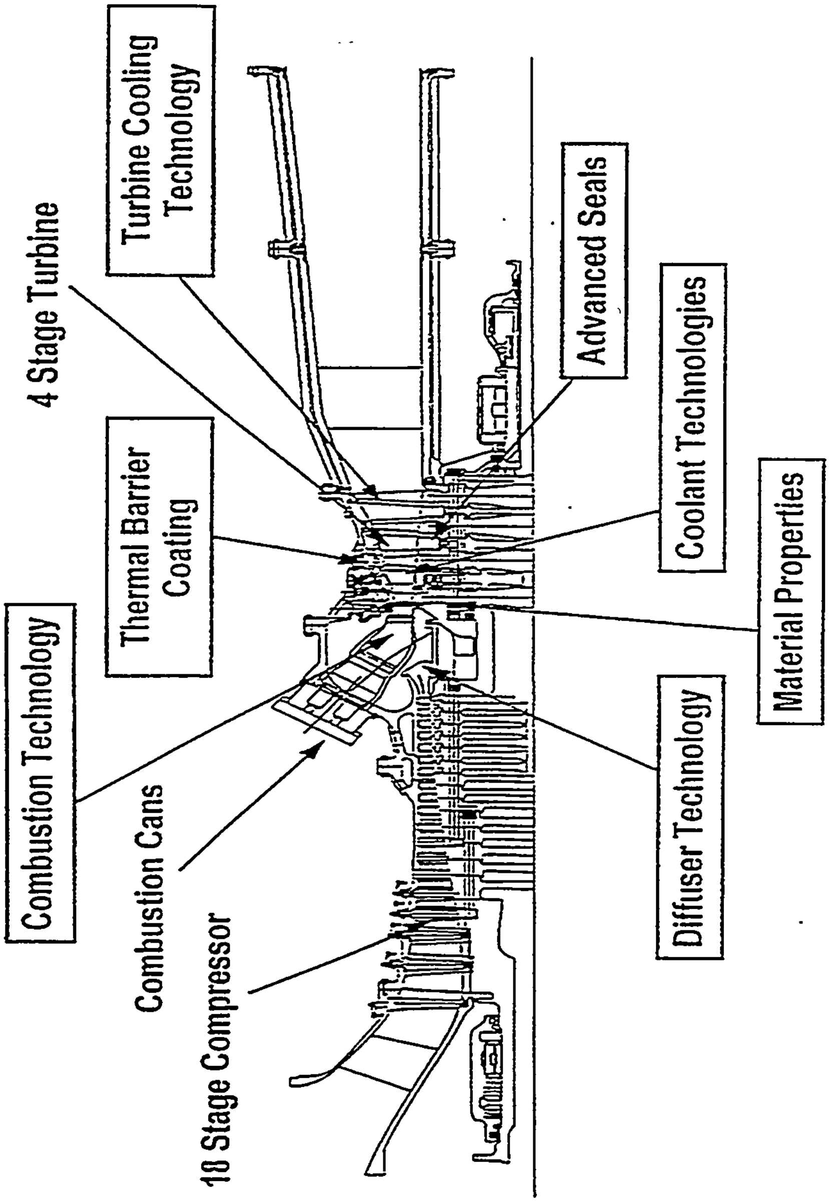

Figure 1-1. Schematic of the H gas turbine cross section

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

SECTION 2.2 (GT) GAS TURBINE DESIGN

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

Section 2.2.2.1 (GTFFCP) Compressor Design

Objective

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

Progress 4Q99 through 3Q98

The 7H aerodynamic design was completed for the airfoil stages and aeromechanics evaluation of the airfoils is 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 mid 4Q99.

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 all rotors were started and are in various manufacturing processes. The projected delivery of all rotors will be in mid 4Q99.

The 7H compressor rig test began in late 2Q99 and was completed in mid 3Q99. Six test phases, including mechanical checkout, initial performance assessment, VSV optimization, part speed operability, power turndown mapping, and high speed surge mapping, were successfully completed. The data reduction was started immediately after the test.

A 7H compressor flowpath was frozen that enabled layouts of the inlet, mid-compressor, and compressor discharge casings, and the tri-passage diffuser to be completed. Electronic data releases (EDR's) fully describing the casing castings as 3D electronic solid models were conveyed to the selected suppliers, who began solidification modeling and pattern work on the respective casings. Conventional casting drawings were initiated. Internal concept reviews were conducted for each casing, and requested improvements were communicated to the suppliers. Preliminary design analysis was completed for each casing, including blade containment, thermal transients, low cycle fatigue (LCF), creep, applied loads (normal and emergency shipping), internal cooling flows, weld life, normal modes, and bolt/flange sizing.

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

Detailed machining drawings defining all the required features for the 7H FSNL Compressor casing were issued. These included all the drawings for the Inlet, Compressor Case, VGV system, CDC, Tri-passage diffuser and CDC Inner Barrel. All machining operations were completed at the suppliers. Mod Machining drawings for prototype test instrumentation have been issued for all components and instrumentation provisions were incorporated into the machining operations.

A detailed, internal design review was conducted to determine that the designs conformed to accepted GE Design Practices. The review showed that the designs meet all the design goals and requirements. Detailed lifing analysis has been completed. Action items from these reviews were incorporated into the casing drawings without schedule impact. In addition, detailed rotor/stator clearance analysis, including the effects of 3D geometry variation, enclosure Delta T, Stator Tube 1G sag, hard stalls, and thermal transients has been completed and minimum clearances required to prevent unacceptable rubbing have been established. VGV kinematics studies evaluating the system sensitivity to tolerance and stiffness variation were completed which showed that the current manufacturing tolerances meet the desired system sensitivity requirements.

All hardware passed the GE quality review for First Piece Qualification (FPQ). In particular, the diffuser dimensional control and material quality were excellent and the diffuser casting is ready for limited production. This represented a significant improvement in producibility from the original 9H concept. All hardware was shipped to Greenville for assembly. Unit assembly drawings, including the stator arrangement, clearance drawing, unit bolting and doweling, unit jacking and alignment, have been initiated and assembly operations are in progress.

Plans for Next Quarter

Unit assembly drawing, including the stator arrangement, clearance drawing, unit bolting and doweling, unit jacking and alignment, will be issued. All stator tube assembly operations and interfaces with rotating hardware will be completed and clearance dimensions verified. The FSNL testing will be initiated.

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 late 3Q99 and be completed in mid 4Q99.

Any remaining life and sealing analysis will be completed.

Technology Application

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

Section 2.2.2.2 (GTFFCB) Combustor Design

Objective

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

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

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

Progress 4Q98 through 3Q99

Development testing of the 9H combustion system was completed in 1999. Eight additional combustor tests were run to minimize combustion dynamics/acoustics and emissions as well as to provide thermal characterization of the hardware. NOx emissions less than 11 ppmvd. at 15% O_2 over the desired load range were achieved with low combustion dynamics, and component temperatures low enough to meet parts life goals. The flameholding resistance of the swozzle based premixers was again demonstrated. Combustor exit temperature patterns were within expectations. The 9H combustion system successfully passed its Preliminary Design Review. At the conclusion of testing, the 9H combustion system also passed its Detailed Design Review.

In addition to the 9H product combustor development, 7H combustion testing was started. The 7H combustion system dynamics responded in much the same way as the 9H system. This meant that the thrust of 7H testing could focus on developing NOx margin below 9 ppmvd. Five tests were run with this objective and encouraging results were obtained.

In addition to the test activities, numerous heat transfer, computational fluid dynamics, and finite element stress analyses were conducted on the component subassemblies. Continued emphasis was directed at the endcover and swozzle subassemblies as well as full-scale combusting flowfields contained by the liner, particularly as they affect the cooling requirements of the liner/cap subassembly. The computational results were compared to measured thermals with good agreement. The resulting lifing calculations for the combustion hardware were predicted to meet goals with substantial margin.

Finally, the 7H transition pieces were fabricated and assembled into the FSNL-1 unit. The transition pieces were installed with only minor fit-up problems. In addition, all DLN production hardware for the 9H first unit was completed.

Plans for Next Quarter

The 7H combustion system testing and substantiation will be completed in the first quarter of next year in GEAE Stand A2. All design analyses for determination of thermal characteristics and stresses will also be completed. Preparations will be made for field testing the first 7H gas turbine. Full speed no load testing of the first 7H gas turbine will be accomplished at the factory. The 9H launch unit will ship to its site with the production DLN system, installation activities will commence at site, and preparations for field testing will be made.

Technology Application

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

Section 2.2.2.3 (GTFFTR) Turbine Rotor Design

Objective

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

Progress 4Q98 through 3Q99

The 7H turbine rotor and steam delivery two-dimensional ANSYS Lumped Fluid Element (LFE) thermal analysis model was completed, with emphasis on optimizing secondary flows, life-limiting features, and rotor stability features. Three-dimensional models were created for all major coponents. Two-dimensional, time-dependent thermal loading boundary conditions were swept onto these models to generate stress concentration factors for three-dimensional features. These stress concentration factors were used in a low cycle fatigue (LCF) program to automatically calculate LCF life throughout the turbine rotor structure.

Three-dimensional ANSYS finite-element models were completed for the majority of the 7H steam system hardware, with preliminary life assessments also completed.

The 7H Turbine Rotor Structural and Steam Delivery System Risk Reviews were completed. The 7H Turbine Rotor and Steam Delivery System preliminary life assessments, including LCF and fracture mechanics analysis, were completed.

All component drawings were completed, and all of the turbine rotor and steam delivery system components were manufactured and delivered to Greenville for assembly in the 7H FSNL test engine.

The Stage 4 turbine wheel / aft shaft rabbet closure is marginal during shutdown. Several DOE studies have been completed to modulate the exhaust frame blowers for rabbet control with some success. The team is currently on hold waiting for 9H FSFL pre-shipment aft end thermal test data to come in.

Plans for Next Quarter

The 7H FSNL test will be run with the turbine rotor and steam delivery hardware.

The current system model will be updated, and various defined mission mixes will be run.

The current lifing model will be updated.

A comprehensive plan to meet the 7H FSFL pre-shipment objectives will be developed.

The 9H FSFL pre-shipment aft-end thermal test data will be analyzed.

Technology Application

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

Section 2.2.2.3.2 (GTFFTR) Wheel Forging Stress Analysis

Objective

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

Progress 4Q98 through 3Q99

A simulation of the 7FA turbine wheel within a rotor system for a typical start-up has been completed for three cases: A pure elastic analysis, an elastic plastic analysis, and an elastic plastic analysis with the effects of the forging process, the machining process and the prespin included. The elastic and elastic plastic results were very similar, but the analysis with the forging and prespin history should significant differences. Areas around the bore showed large reductions in stress, but regions near the rabbet fillets showed significant increase in stress. One conclusion made is that the effect of forging and prespin residuals is very component and process dependent.

Plans for Next Quarter

Chief engineer review.

Determine a method to incorporate this effect into the current rotor analysis methodology.

Technology Application

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

Section 2.2.2.3.3 (GTFFTR) Rotor Steam Circuit Analysis

Objective

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

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

Progress 4Q98 through 3Q99

The first CFD analysis of the 7H supply and return manifolds was completed, and the results are very encouraging. The pressure drop in each 7H manifold is lower than the target set for the 9H manifolds as a result of the realignment of first-stage and second-stage incoming jets, the more aerodynamic contour of the manifolds, and the addition of guide vanes—all lessons learned during the 9H design activity.

The CFD simulation of the latest 7H and 9H supply bore tube designs was also 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 7H design is better than that of the previous 9H design. Despite the fact that the previous design operated at a lower flowrate, 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 is similar to 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. 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 result 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.

The swirl angle for the 7H design remains at a significantly lower value than the results obtained from the 9H calculation. The strut does not exert as great an influence on this parameter as it did for the 9H.

A CFD analysis of the high-pressure packing upstream cavity was recently performed, and a converged solution has been obtained. In the course of the solution process, however, it was necessary to impose a fictitious wall on part of the outlet that leads to the compressor flow path to prevent inflow through this exit boundary. This is an indication of the possibility of flow reversal through this outlet and, hence, from the compressor flow path. This led to a closer examination of the flow in the neighboring region and indeed evidence of this potential flow reversal near the stator wall is present. It has been determined that the amount of flow reversal predicted by the analysis is less than 5% of the net outflow and therefore not expected to carry any adverse consequences. Furthermore, a design feature present in the design but not modeled in the analysis may further reduce this potential flow reversal or completely eliminate it. This result has been transmitted to Design Engineering.

Plans for Next Quarter

The redesign of the bore tube is currently underway at GEPS. When the most recent drawings are received, the CFD analysis of the new configuration will be started. The design drawings of the latest 7H manifolds are necessary in order to confirm their hydraulic performance using CFD.

Technology Application

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

Section 2.2.2.3.5 (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 4Q98 through 3Q99

Optical properties of TBC and TBC-coated buckets returned from field testing were measured and the results applied to a model to estimate the surface temperature of the TBC from pryrometer data.

The second-stage buckets have been equipped with platinum marks to aid in the estimation of surface temperature and to verify the line of sight during the full-speed full-load (FSFL) pre-shipment test.

Plans for Next Quarter

TBC-coated buckets will be returned to service. Additional information will be gathered on the time-dependence of changes in TBC optical properties.

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 4Q98 through 3Q99

Return Manifold Testing

Evaluation of the return manifold was completed this year. Manifold flow distribution and pressure loss were measured. Design specifications for pressure loss and flow uniformity were determined by calculations using CFD and YFT. The tested manifold met the design specification for pressure drop but did not meet the requirement for flow distribution. As a result, the manifold design was modified to achieve uniform flow distribution through the manifold. The redesign was completed using CFD modeling and no further testing was deemed necessary.

Spoolie Dynamic Pressure Testing

Testing of the steam circuit to determine whether system dynamics pressures have a detrimental effect on spoolie joint performance was completed this year. One concern is that coherent flow instabilities (i.e., tones) coupled with system natural frequency response would accelerate wear and fatigue of cooling system parts, particularly the spoolies. A test was devised and built to measure the dynamic pressures in a portion of the steam supply system. The test included an axial tube, a supply manifold, a bucket tube, and a bucket. There were three spoolie couplings: one connecting the axial tube to the inlet of the manifold, one connecting the exit of the manifold to the bucket tube, and one connecting the bucket tube to the inlet of the bucket. Seven dynamic pressure transducers were installed in the system to measure the dynamic pressure that acts on the spoolies. 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 to 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 and joint misalignment. During these tests the axial tube was deliberately misaligned and the tests were repeated. 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.

Bore Tube Dynamic Pressure Testing

The bore tube dynamic pressure testing was focused on flow instabilities that may cause excessive wear of cooling system parts. The concern is that the flow passing through the bore tube supply passage and passing over the support struts may produce discrete tones that could couple with the system natural frequency response. The flow-induced pressure oscillations were evaluated in this test; the bore tube system natural frequency response (or system resonance) was evaluated in a field test. To investigate these oscillations, a full-scale model of the bore tube was constructed. The bore tube was connected to a test stand where an earlier bore tube design was tested. Dynamic pressure transducers were installed at seven locations in the bore tube. A shakedown test was completed, and the model and test stand performed as expected. At that time a design change in the bore tube was deemed necessary and all testing stopped. No decision has been made about testing the new bore tube design.

Bore Tube Acoustic Resonance Field Test

Measurements of the bore tube acoustic resonance were made in the 9H gas turbine at the GEPS Greenville, SC, facility. The objective of these tests was to search the bore tube supply and return ducts for acoustic resonances that might exist and lead to high-cycle fatigue or other operational problems. The approach was a combination of experimental and analytical techniques.

Loudspeakers were set into specially designed baffles, and the supply and return ducts were individually excited with high-level, broadband noise. Microphones measured the acoustic frequency response of the bore tube acoustic cavity at several locations in both ducts. Many individual peaks indicating resonances were observed, not all of which could be categorized.

Using a combination of analytical methods, a number of these resonances with particular modes of acoustic standing waves in the bore tube were identified. Then frequency-scaling was performed on these resonance peaks to estimate the peaks expected under the temperatures and pressures of actual turbine operations. None of the resulting scaled frequency peaks stood out as potentially harmful, as they did not correspond with known structural or flow-induced excitations of the turbine. The excitation of the remaining unidentified modes is not presently thought to be a problem because of the lack of an observed or calculated driving frequency in turbine operation.

Plans for Next Quarter

This task was completed in 2Q99.

Technology Application

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

Section 2.2.2.4 (GTFFTB) Turbine Bucket Design

Objective

The objective of this task is the design of buckets for the four rotating stages. The heat transfer and material databases for steam-cooled first- and second-stage buckets continue to expand and will be integrated concurrently with the design. Cooling passages will be sized consistent with manufacturing practicalities and the bucket life requirements. Flow variation and consistency will affect life calculations and will be considered. Current practices for thermomechanical steady-state and transient analyses, dynamics and vibration analysis (which can deal with anisotropy), and corrosion/oxidation analysis will apply throughout. Drawings and specifications will be developed in preparation for manufacturing.

Progress 4Q98 through 3Q99

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 4Q98 through 3Q99

The experimental facility used in the present study is a cold-flow, steady-state blade cascade comprising three airfoils and two airfoil flow passages. The cascade is stationary. The cascade was reconstructed with narrower blade tip geometry and tested to assure proper operational characteristics for flow distribution and tip heat transfer.

Heat transfer measurements were made using the steady-state liquid crystal technique. An etched foil heater was used to provide a uniform heat flux. Heater local temperatures were measured using a Mylar-backed 0.005-inch-thick liquid crystal sheet applied over the heater with a thin layer of adhesive (0.001 inch). The liquid crystal used was Halcrest R40C5W, which was calibrated for hue vs. temperature. An RGB camera was used to take both calibration and test images, and the results were reduced to temperatures. A wattmeter was used to measure heater power. The temperature drop through the adhesive and Mylar was then calculated to obtain airfoil tip local temperatures. Heat transfer coefficients were measured on approximately 75% of the flat surface of the blade. A heat loss test was performed and the loss into the airfoil was approximately 8 to 10% of the total power into the heater. All results were corrected for this loss.

In 2Q99 and 3Q99 a smooth radiused edge (R.090 inch) blade tip was tested as well as four alternative tip seal geometries. Heat transfer coefficients varied slightly with tip gap in the leading edge region of the blade but converged near the trailing edge. The heat transfer and pressure measurements for the tip seal geometries showed improvements in leakage and a reduction in heat transfer.

Plans for Next Quarter

Three sets of tests are planned for 4Q99. A square edged airfoil and two alternative tip seal geometries will be tested.

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 4Q98 through 3Q99

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.

The CFD analyses of the platform cavity region flow and heat transfer were executed this year with engine-scale geometry and conditions, including rotation. Data post-processing was completed, and the results provided to the GEPS design team. In general, for the specific cooling design and strength involved in this technology: (1) CFD heat transfer results for the platform cold-side surfaces were within about 20% of the experimental results obtained in the stationary model tests, except for the immediate impingement zone; the disagreement in the primary impingement region is not surprising, given the limitations of CFD modeling. (2) The addition of rotational effects in the CFD flow and heat transfer predictions had negligible effect (i.e., no detrimental effects) on the resulting heat transfer cooling performance for the platform region of interest.

Experimental efforts in the present reporting period were on hold pending the completion of the improved platform cooling design; no test section modification or testing took place

Plans for Next Quarter

In 4Q99, Design Engineering is expected to select a revised platform cooling design so that work can begin on the modification of the existing model test section in preparation for validation testing.

Technology Application

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

Section 2.2.2.4.8 (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.

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

Progress 4Q98 through 3Q99

The friction factor and heat transfer coefficient data existing in the GEAE-CRD database and in the open literature were collected and analyzed. The data were correlated using passage geometric variables and the flow Reynolds numbers. The results obtained imply that the Nusselt number correlation has an acceptable uncertainty, but the friction factors will have to be experimentally verified by running flow tests with a cast leading edge passage and determining their relation to the correlation predictions. The correlation task for the bucket leading edge turbulated passage friction and heat transfer is finished.

Plans for Next Quarter

This task was completed in 4Q98.

Technology Application

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

Section 2.2.2.5 (GTFFTS) Turbine Stator Design

Objective

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

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

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

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

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

Progress 4Q98 through 3Q99

Boundary conditions, design approaches and assumptions were approved by the Design Review Team. An initial Manufacturing Review was held with the Manufacturing Review Team. Flow and heat transfer analyses were completed and indicate the design meets trailing edge air flow, steam flow, steam temperature rise, and steam pressure drop requirements. Finite element analyses and insertability studies were completed and indicate acceptable airfoil rib configurations. Preliminary casting trials were initiated on both Stage 1 and 2 nozzles.

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.

Manufacturing development activities were initiated. Prototype airfoil casting trials, using cores made from rapid tooling and SLA patterns were initiated for both stages. Prototype cover casting programs were also initiated for both stages. Joining and Thermal Barrier Coating (TBC) development activities were also initiated.

Plans for Next Quarter

Thermal, stress, life, sealing and cooling analyses will be refined. Designs will be adjusted to improve capabilities relative to CTQ requirements. Teams will continue to release production sub-component, machining and assembly definitions to support production schedules.

The production airfoil casting tooling cycles will continue with initial ceramic core trials and subsequent casting trials to follow when tooling complete.

Manufacturing development activities will continue for airfoil castings, cover castings, joining and TBC. Additional manufacturing development activities will be initiated for other sub-components including steam exit hardware, impingement plates, airfoil inserts and various machining and joining operations.

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 4Q98 through 3Q99

Exhaust Frame and Diffuser

Exhaust Frame fabrication, frame mod machining for prototype instrumentation, machining, radiation shield layouts, diffuser and arrangement drawings were completed.

A detailed, internal design review was conducted to determine that the design conformed to accepted GE Design Practices Internal. All action items were incorporated into all released drawings. The review showed that the design meets the design goals and requirements except for the LCF life of the Inner Barrel horizontal joint. Vibration analysis and bolted joint analysis has been completed to support release of the machining drawings. Several additional analyses were identified during the Tollgate 4 review in February. These analyses included the cooling/purge flow analysis and transient thermal analyses of the diffuser, frame and assembly components.

Welding of the Exhaust Frame fabrication components has been completed at the supplier and has been heat-treated. Instrumentation Modification Machining drawings were completed and were to the supplier to pre-drill holes and other features required for instrumentation. Insulation drawings for the Inner Barrel and Struts were issued. 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 from the supplier. All hardware passed the GE quality review for First Piece Qualification (FPQ).

Follow-on analysis showed that insulation on the outer barrel would significantly reduce heat rejection and reduce metal temperatures.

The fabrication of the Exhaust Frame was completed in April. The frame was then heat-treated and machining began the second week of May. The machining was completed the third week of June. The forward diffuser fabrication was started at the end of April and finished in July. Instrumentation of the frame began at the end of June. Exhaust Frame assembly drawings have been issued, and assembly operations are in progress.

Steam Gland

The Steam gland has been poured and casting qualification have been completed. The casting passed First Piece Qualification (FPQ) at the supplier. Machining drawings were issued and communicated to the supplier. Instrumentation definition drawings were defined and issued. Machining operations, including prototype test instrumentation, have been completed. 2D finite element transient heat transfer and life analysis has been completed. All hardware passed the GE quality review for First Piece Qualification (FPQ). All hardware was shipped to Greenville for assembly.

#2 Bearing Housing

Detailed machining drawings defining all the required features for No 2 Bearing Housing were issued. All machining operations were completed at the suppliers. Mod Machining drawings for prototype test instrumentation have been issued and instrumentation provisions were incorporated into the machining operations.

A detailed, internal design review was conducted to determine that the designs conformed to accepted GE Design Practices. The review showed that the designs meet all the design goals and requirements.

All hardware passed the GE quality review for First Piece Qualification (FPQ). Bearing Housing assembly drawings have been issued and assembly operations are in progress.

Plans for Next Quarter

Exhaust Frame and Diffuser

Design of the Aft Diffuser Duct (AO42) and the required drawings will be initiated. Life analysis of the Inner Barrel diffuser horizontal joint and carrier flange will be completed. Assembly operations for FSNL-1 will be completed.

Steam Gland

Assembly operations for FSNL-1 will be completed. 3D life analysis, including the effects of thermal transients, weld life predictions and horizontal joint sealing will be completed.

#2 Bearing Housing

Complete assembly operations for the 7H FSNL test.

Technology Application

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

Section 2.2.2.7 (GTFFMS) Mechanical System Design

Objective

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

Progress 4Q98 through 3Q99

The focus of work was on preparation for the 9H full speed, full load (FSFL) pre-shipment test, and the 7H preliminary and detail design and manufacturing.

The 9H Gas Turbine assembly was completed and the unit shipped to test for assembly into the test facility.

Detail design of the 7H was completed, and component hardware manufacture was completed allowing the start of unit assembly. 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 completed, reflecting the final 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

Complete the 9H FSFL preshipment test and the 7H unit assembly. The 7H unit will be installed in the test stand and the FSNL test will begin. Customer support will continue, ensuring that the final H configuration meets the customer's needs.

The 9H gas turbine will be prepared for shipment.

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 4Q98 through 3Q99

9H: All on-base piping, turbine base, and electrical documentation required for the second FSNL test was completed and the resulting hardware installed on the FSNL test unit. Actual installation at the test stand went smoothly as a result of the design process, fit-up activities included prior to the first FSNL test, and the actual first FSNL test.

7H: Completed all critical designs required for first FSNL test. Completed Formal Design Review of those designs with the Chief Engineers Office. Feedback factored into the affected designs. All critical hardware drawings required for first FSNL test released and hardware on order.

Plans for Next Quarter

9H: Support of the 9H FSFL pre-shipment test at test stand. All data from the FSFL pre-shipment testing will be reviewed. The results will be applied as applicable to all affected hardware designs, documentation, and the actual hardware required for the final product.

7H: Support of first 7H FSNL test at test stand. All data from the first FSNL testing will be reviewed. The results will be applied as applicable to all affected hardware designs, documentation, and the actual hardware required for the 7H FSFL pre-shipment test and final product.

Technology Application

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

Section 2.2.2.9 (GTFFIT) Instrumentation and Test

Objective

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

Progress 4Q98 through 3Q99

The 9H gas turbine compressor was rebuilt after successfully completing the FSNL factory test. A new compressor aft shaft and instrumented compressor blades and wheels were added, in addition to the instrumented compressor rotor, turbine rotor, and turbine nozzles and buckets. This additional instrumentation will reconfirm the compressor performance of the FSNL test, as well as provide the standard protective instrumentation for engine monitoring.

After the instrumentation and rebuilding tasks were completed, the 9H gas turbine was moved from the Greenville manufacturing area to the test stand. The 9H unit was aligned in the test stand with the drive motors, steady rest bearing, and newly developed telemetry system, which will extract all rotating sensor signals. All skids and accessories were connected to the data acquisition system, and the Mark VI control system was checked out in preparation for a 4Q99 FSFL pre-shipment test date.

In preparation for testing, a number of design reviews were conducted, including a "Test Risk Work Out", a Safety Review, and several Red Flag reviews for the Test Plan, gas turbine flange-to-flange components, test stand, constrol system, test stand skids, accessories, and piping. Based on these reviews, there are no problems anticipated in starting the 9H FSFL pre-shipment test as planned.

The 7H FSNL test CTQs, compressor and protective instrumentation, and unfired and fired test runs were defined for the December 1999 FSNL factory test.

Plans for Next Quarter

The 9H gas turbine FSFL pre-shipment factory test will be completed. The unit will ship to the customer site next year.

The 7H FSNL test plans and test instruction documentation will be completed this quarter. The Red Flag review for 7H FSNL factory test is planned for mid-October. The 7H FSNL test will begin in late December.

Technology Application

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

SECTION 2.2.3 (GTET) TECHNOLOGY VALIDATION

Objective

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

Section 2.2.3.2 (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 4Q98 through 3Q99

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 that can significantly increase leakage.

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

Progress 4Q98 through 3Q99

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

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

Plans for Next Quarter

One additional test will be run to complete the Design of Experiments matrix.

Technology Application

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

Section 2.2.3.4.3 (GTETRH) Rotating Trailing Edge Heat Transfer Tests

Objective

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

Progress 4Q98 through 3Q99

Testing and data reduction of the 7H second-stage bucket trailing edge passage model run in the rotational test rig were completed, and a report was prepared for Design Engineering.

Plans for Next Quarter

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 (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 4Q98 through 3Q99

Tests were performed at three different passage average inlet Reynolds numbers on a 2X-scale acrylic test model designed and fabricated for use with the liquid crystal test technique. A consistent set of full-surface heat transfer coefficient data was obtained for the highest laboratory flow. These results were scaled to turbine operating conditions—including the conversion from laboratory air to steam—to provide a full set of thermal boundary conditions for design analysis. All results and conclusions regarding heat transfer distributions within the various regions of the passage, and their implications for the second-stage bucket design, were transmitted to GEPS Design Engineering.

The 2X-scale acrylic test model was then refitted with static pressure taps. Data were acquired at the same three Reynolds numbers for which heat transfer data were taken previously. These data were then compared to 1D flow predictions used by GEPS to model the internal cooling passages of the bucket. A fundamental change in modeling strategy was implemented as a result of these data, and overall agreement improved significantly.

One second-stage bucket, which had been tested previously, was refitted with many additional static pressure taps. The trailing-edge cavities of another second-stage bucket were cut away from the bucket to form individual, single-tube test pieces which were also fitted with pressure taps and tested.

A new tip-turn internal cooling circuit configuration was identified, and the existing liquid crystal model retrofitted to the new configuration. Heat transfer measurements were made, and the results were submitted to GEPS engineers to adjust and validate the internal heat transfer boundary conditions.

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

Plans for Next Quarter

This task was completed in 3Q99.

Technology Application

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

Section 2.2.3.5.8 (GTETIH) S1N Trailing Edge Heat Transfer Tests

Objective

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

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

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

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

Progress 4Q98 through 3Q99

The film holes covering part of the trailing edge region near the rib are at an angle of 30° to the flow and drilled at an angle of 90° to the wall. Due to manufacturing constraints, these film holes are drilled in such a way that the film flows in the film holes are co-flowing with the supply cavity side feed flow in the airfoil half near the outer sidewall region. The film flows are counter-flowing to the supply cavity flow in the airfoil half near the inner sidewall region. Information in the open literature shows that the film hole discharge coefficients depend on the supply side velocity (Mach number) and orientation of the film holes with respect to the supply cross flow. A test facility was designed and experiments were conducted to measure the discharge coefficients of 30°-inclined film holes as a function of pressure ratio, supply side Mach numbers, and co- or counter-flowing supply flow with respect to the film flow direction.

Additional film hole discharge coefficients were measured during 1Q99. The results showed the dependence of the discharge coefficients on three parameters: the supply flow Mach number, flow direction with respect to the film hole angle, and the ratio of the supply pressure to the discharge pressure across the film holes.

For the work on cooling the trailing edge of the first-stage nozzle, each vendor manufactured one STEM-drilled turbulated passage. The test specimen provided was turned into a 0.25-inch OD tube. Before the tube was instrumented, an x-ray image was recorded to locate the beginning and end of the turbulated region. The test tubes were then instrumented with static pressure taps and imbedded thermocouples before the flow and heat transfer tests were run. The test results from one tube provided information that could be related to the existing data. The results obtained with the second tube did not agree with the expectations. The second tube was then cut along a diameter and visual observations revealed that the tube was not manufactured according to the specifications.

Plans for Next Quarter

A second test tube will be manufactured according to specifications and tested.

Technology Application

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

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

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

Objective

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

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

Progress 4Q98 through 3Q99

Flow tests were completed earlier with cast first- and second-stage buckets, four of the impingement inserts of the first-stage nozzle cooling circuits without and with inlet metering orifices, and for the turbulated convective cavity with two cast first-stage nozzles. In 4Q98, similar flow tests were conducted with development and production impingement inserts for cavities 1, 2, and 3 for the second-stage nozzle. In addition to the insert flow test, a doublet of the second-stage nozzle was assembled with all the flow elements and instrumented with pressure taps. The static pressure distributions at various circuit locations were measured with all cooling circuit elements assembled.

Tests were performed to verify the methods used in the design of the impingement inserts for the first-stage nozzle used in cooling cavities 1, 2, 3, and 4, and to measure the impingement jet supply pressure distributions along the insert from root to tip. Similar flow tests were also conducted with the cavity 1, 2, and 3 inserts (development and production parts) for the second-stage nozzle. A doublet of the second-stage nozzle was assembled with all the flow elements and instrumented with static pressure taps. Flow and pressure drop distribution tests were conducted with this second-stage nozzle doublet and results were compared with the flow models.

During 1Q99, flow tests were performed with cast 9H first- and second-stage nozzles and the various cooling circuit impingement inserts, without and with inlet metering orifices.

Six first-stage nozzle impingement inserts were tested in cooling cavities 1 through 6. The objectives of these tests were (1) to verify the methods used in the design of the inserts and the impingement jet supply pressure distributions along the jet supply flow areas and (2) to compare the results of these production parts with the development parts tested earlier. The results showed that the average pin-checked jet diameters were close to the required values. The static pressure distributions at the various jet row locations were similar to those measured earlier on the development parts. Some variations in measuring insert flowrates with respect to design requirements were noted. The inserts were then incorporated into the cast airfoil, the inner and outer sidewall impingement plates and covers were assembled, and flow tests were run for the overall flow circuit.

Similar flow tests were conducted with the impingement inserts of the second-stage nozzle without and with metering plates. The inserts were then incorporated into the cast airfoil, the inner and outer sidewall impingement plates and covers were assembled, and flow tests were conducted for the overall cooling circuit. Flowrates were measured as a function of inlet-to-discharge pressure ratio. Static pressure taps were positioned at key locations of the cooling circuit, and the pressure distributions were measured as a function of flowrate or pressure ratio.

The static pressure data and the flowrate data recorded for the first- and second-stage nozzles were compared with the flow models. The comparisons were used in altering the flow resistances where needed and to anchor the design predictions compared with the cast component flow data. In order to evaluate the effect of some of these changes on the resulting metal temperatures, GEPS staff applied the thermal conduction models of the nozzles with the empirically validated flows.

The flow tests on the first-stage nozzles of the 9H gas turbine that will be used in the tests at GEAE, Evendale, were initiated with available cast components. The first series of tests concentrated on determining the flow distribution underneath the outer sidewall impingement plate. The post-impingement flow distributes itself between leading edge cavity 1 and cavities 6 and 7 in the trailing edge region. Tests were conducted with half and all the impingement holes open and the flow going through cavity 1 only, cavities 6 and 7 only, and all cavities. In addition to the overall flows, static pressures were also measured at thirteen locations at the outer sidewall post-impingement regions.

Six impingement inserts for each of the six cavities have been received. Flow tests were conducted with and without the inlet metering plates. Two inserts were selected for each of the six cavities, which satisfies the design requirements.

Plans for Next Quarter

The next series of flow tests at Evendale will be conducted with the nozzle assemblies.

Technology Application

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

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

Section 2.2.3.5.12 (GTETIH) Nozzle Fillet Heat Transfer

Objective

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

Progress 4Q98 through 3Q99

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

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

Plans for Next Quarter

Design Engineering will complete their evaluation of improved or re-designed regions, at which juncture one or more models will be designed for validation testing, fabricated, and then tested. The validation and optimization testing of such fillet regions of the first-stage nozzle may also be extended to other internally cooled features of the nozzle design.

Technology Application

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

Section 2.2.3.5.13 (GTETIH) S1N and S2N Endwall Heat Transfer

Objective

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

Progress 4Q98 through 3Q99

Two 2-inch × 2-inch test plates were manufactured from GTD222 and N5. The test plates were coated with the brazed microturbulators. The roughness of each test plate was characterized by means of a cone profilometer. The test plates were instrumented with imbedded thermocouples. The first tests were conducted with the GTD222 rough test plate and two representative jet plates at several average jet Reynolds numbers. Baseline tests were also conducted with a HastX smooth test plate and with the same two jet plates. The results provided enhancement values at the test conditions. The second series of tests were conducted with the N5 test plates and the same jet plates. The enhancement values obtained during these tests are lower than the ones measured earlier with similar rough surfaces. This difference is attributed to the effect of the distance between the impingement jet plate and the test plate. All previous tests were conducted at impingement distance/jet plate diameter values of approximately 3. In the present tests this value was chosen to be 5.

The impingement heat transfer enhancement values obtained with the brazed microturbulators were reported to GEPS design staff.

Plans for Next Quarter

This task was completed in 3Q99.

Technology Application:

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

Section 2.2.3.8 (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 4Q98 through 3Q99

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.

Coolant System Flush

An apparatus was completed containing a first- and second-stage bucket pair, with cross-tube, rotor manifold, axial tube, and radial tube components to determine flush feasibility.

The apparatus is divided into two skids, a flush supply and a specimen rack sub-systems. The two subsystems will be connected by flexible feed- and return-hoses during experimental operation. The flush supply skid fabrication process was inspected in late August, and the system was shipped to the GEPS Houston Service Shop in mid September. It will be used for preliminary tests on real stator production hardware there in 4Q99. The specimen skid is awaiting further design instructions from Greenville but will be shipped to Houston in 4Q99. A vendor who proposes using foam as a cleaning medium will be given the opportunity to demo his process using the specimen skid in Houston.

Plans for Next Quarter

Consultation will continue on application of the cleanliness measurement system on the Greenville floor as requested. Work will continue with attorneys on patent application. Assembly and qualification of the surface cleanliness measurement equipment at Houston will be overseen. GEPS staff will be assisted in commissioning a new flush test rig at Houston and analyzing results.

Technology Application

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

SECTION 2.2.4 (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.

Technical Progress

The creep testing in steam at various temperatures for Ingot 4 material concluded with various test times for each temperature. 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. Dynamic threshold testing of wrought 718 was completed and static threshold tests of the same material were initiated.

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 cast coarse grain slabs, cast 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, 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 evaluated in the test laboratory.

Plans for Next Quarter

Continue hold time LCF tests in steam on cast 718 material. Complete dynamic threshold tests in steam and begin steam static threshold tests in the next reporting period.

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 4Q98 through 3Q99

Various meetings and discussions with manufacturer of compressor discharge diffuser. Approved First Piece Qualification (FPQ) documentation and castings.

Plans for Next Quarter

This activity was completed in 3Q99.

Technology Application

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

Section 2.2.4.7 (GTMTRF) Turbine Rotor Forging Materials and Processes

Objective

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

Progress 4Q98 through 3Q99

A large diameter 718 ingot was melted to test conditions to promote the presence of microstructural conditions of interest. Three sub-scale forgings were made from this material. These forgings, along with the Stage 3 turbine wheel from an earlier test rotor and a supplier's prototype forging were 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 were taken from the above material for additional tests. Various evaluations of supplier forgings were made over the past year. Two new large diameter ingots were recently melted for evaluation of processing revisions.

Hold time Low Cycle Fatigue (LCF) tests, in air, of Ingot 4 were conducted over the past year. One specimen has exceeded 7,875 cycles. A radially oriented specimen is still running with 1,162 cycles as of this report. Comparable tests of Ingot 3 material, the FPQ forging, were completed. 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 reported to Design Engineering.

Plans for Next Quarter

Continued evaluation of supplier ingot and forge material. Select test conditions in creep rupture, hold time LCF and crack growth will continue into the next quarter.

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 4Q98 through 3Q99

First Piece Qualification (FPQ) packages were reviewed and approved for the stator and rotor manifolds and elbows. A part specification for the manifold was issued and subsequently revised to reflect lessons learned from the shop. 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.

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

Monitor productionizing of designs and modify specifications to incorporate lessons learned where applicable.

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 4Q98 through 3Q99

Long term creep tests on various hot gas path materials were conducted over the course of the year. 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 (10) creep (11), tensile (14), Low Cycle Fatigue (LCF) (18) and High Cycle Fatigue (HCF) (19). Additional slab material was recently obtained to permit continued testing.

Plans for Next Quarter

Complete machining of test specimens from two heats of the third and fourth stage bucket material. Complete additional creep tests on this material as well.

Technology Application

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

Section 2.2.4.10.1 (GTMTTA) Airfoil NDE

Objective

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

Progress 4Q98 through 3Q99

Wall Thickness Measurement

Quantitative infra-red (IR) wall thickness imaging methods have been modified for the inspection of single-crystal and directionally-solidified ATS gas turbine airfoil castings. Measurement capability trials have been conducted using this full-field IR method for wall thickness measurement in step wedge samples as well as actual airfoil castings produced for the ATS gas turbine. A simple user interface has been prepared for the inspection of the production airfoil castings for the ATS gas turbine.

Detection of Internal Casting Defects

Immersion ultrasonic imaging and film and digital radiography have been evaluated for the inspection of ATS gas turbine airfoil castings for internal casting defects. As a result of these development and evaluation programs, digital radiography has emerged as a practical method for enhanced inspection of ATS gas turbine airfoil castings for internal casting defects. Both amorphous Selenium and amorphous Silicon digital radiographic imaging systems have been tested in inspection capability trials on the first stage turbine airfoils (both bucket and nozzle) for the ATS gas turbine. Test samples have been prepared by machining 'pore-like' blind holes (depth = diameter) in the airfoil & fillets of actual ATS gas turbine airfoil castings. Probability of detection (POD) curves have been generated from the inspection capability data for both film-based and digital radiography inspection methods.

Weld Inspection

An ultrasonic inspection method has been developed and implemented for the inspection of the cover-to-nozzle welds in the first stage nozzle assembly of the ATS gas turbine.

Plans for Next Quarter

The characterization of the measurement capability of the quantitative IR method for full-field wall thickness imaging of the ATS gas turbine airfoil castings will be completed. The comparison of the inspection capability of digital X-ray vs. film X-ray methods for nondestructive evaluation of the ATS gas turbine airfoil castings will be completed. Consultation will continue, as necessary, on the application of the ultrasonic inspection method for nondestructive evaluation of critical weld joints on the ATS gas turbine nozzle assembly.

Technology Application

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

Section 2.2.4.15 (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 4Q98 through 3Q99

Continued refinement of the braze and weld repair processes for first and second stage airfoil materials. Completed screening tests of the first stage nozzle cover joint and selected two processes for additional evaluation. Completed screening tests for the stage two nozzle cover joint. Completed stage one bucket tip cap joint tests and issued a report to Design Engineering. Completed first and second stage bucket root cover plate tests. Completed stage 1 nozzle end cover base metal tests to help evaluate the resulting joint behavior. Continued various analyses of the affect of defects on the performance of key joints in service conditions.

Plans for Next Quarter

Studies will continue to evaluate and enhance repair methods for hot gas path materials with selection of process and subsequent optimization of parameters. Complete first and second stage nozzle tests to evaluate four joining processes. Complete first and second stage bucket tests to evaluate six joining processes. Initiate testing of first stage shroud, first stage bucket shoulder and first stage bucket trailing edge joints. Continue defect correlation.

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 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 4Q98 through 3Q99

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 have been established; including installation, calibration, and programming, to assure that process transfer among the different cells can be readily accomplished.

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

Robot alignment and calibration time was reduced by a factor of four using the new DynaCal™ System. A filter to correct the robot paths for the effects of variation in true part position due part-to-part dimensional variation and fixture alignment variation was developed and demonstrated. 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.

Coating Processes for ATS Components

COATING PROCESSES WERE DEVELOPED AND QUALIFIED FOR THE FOLLOWING ATS COMPONENTS:

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

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

Bond Coat Processes

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

A) Thermal spray bond coats

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

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 were also performed 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. A pilot CVD coating reactor was installed at GECRD to coat ATS nozzles for cascade testing. Long-term durability testing is being performed using the JETS and BECON thermal gradient test rigs.

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

A) Surface finishing methods

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

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

Gage Repeatability and Reproducibility studies were performed for both the Huffman Touch Probe (TP) system and GE Eddy Current (EC) measurement systems. A computer simulation study was performed to define the work envelope, fixturing, and tooling requirements for ATS buckets and nozzles. All parts can be processed on the modified grinding system using a single setup. Grinding trials on ATS buckets have begun.

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. A second alternative finishing technique that utilizes part-specific soft tooling and conformable abrasive media demonstrated promising results on flat samples and the suction side of a bucket. Soft tooling was 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. Final process qualification is nearly complete, but some difficulties have been encountered as a result of dimensional variation in the early parts.

C) Cooling holes

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

A study was begun to determine the type and quality of coating coverage that can be achieved on trailing edges of nozzles with cooling holes. This study is aimed at determining the effect of two spray motions in combination with different cooling hole exit geometries.

TBC Process and Diagnostics

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 longer standoff distances and up to 5X higher powder injection rates. Plazjet guns were installed in two GE spray cells, and will be used for both production and process development. A new spray process was developed at GECRD and successfully transitioned to manufacturing, resulting in improved TBC thickness and surface finish as well as reductions in process cycle time of nearly 3X for production hardware. Process development was greatly accelerated through leveraging of diagnostic tools developed in a recently concluded ATP program.

A comprehensive TBC process/properties database is being accumulated, including tensile, modulus, deposition rate, thermal conductivity, surface roughness, and furnace cycle life. Regression models to predict TBC properties, including both mean and standard deviation, from the controlling process parameters are being developed as part of the GE "Design for Six Sigma" (DFSS) initiative. GECRD is an industrial member of the Thermal Spray Consortium at the University of Toronto, which is developing transfer functions to predict TBC microstructure evolution using advanced experimental, numerical and statistical methodologies. Simulation software developed by the consortium will be beta tested by GECRD in 2000.

Non-destructive TBC Thickness Measurement

An automated ceramic coating thickness measurement system consisting of a flexible eddy current probe in combination with a multi-axis contact probe scanner was developed. Installed Coordinate Measuring Machines (CMMs) are used as the scanning devices. Several hundred inspection points can be measured in under fifteen minutes, which reduces inspection time by over 5X compared to manual measurements.

An improved flexible eddy current probe is being developed, both to reduce the probe cost and to improve the probe durability. A probe contact simulator, consisting of a single axis actuator with a servo controller is being developed in order to test probe life.

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

Non-destructive TBC Microstructure Evaluation

Laser Ultrasound (LUT) is being developed for non-destructive evaluation (NDE) of TBC microstructures. 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 as well as production buckets and thermal-mechanical fatigue (TMF) test specimens were extensively evaluated to further validate and refine these correlations. Good correlations were observed between LUT tensile predictions and destructive pull-tests for coupons. However, some of the microstructural variation present on the components resulted in loss of signal due to attenuation, as well as a different transfer function from that obtained on the coupons. As a result of these inconsistencies, software for coating "fingerprint" evaluation was developed. This software compares the LUT signature for an unknown coating with a database of signatures from coatings of different microstructures. The signature that most closely matches the unknown coating is selected from the database, resulting in predictive accuracy for coating tensile strength of 10-20%.

Quality Function Deployments (QFDs) were performed with engineering, manufacturing and services to define the functional requirements for the LUT system. Cost reduction of the instrumentation was very important. A low cost Sagnac interferometer developed jointly by Northwestern University and GECRD meets all initial requirements. The prototype instrument will be delivered to GECRD in 4Q99. 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 GECRD 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

Evaluate calibration filter on ATS hardware.

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

Part Coating

Coat ATS production stage one nozzles and welded joints of ATS stage two nozzles.

TBC Manufacturing Technologies

Demonstrate CNC grinding capability for ATS buckets.

Non-destructive TBC Thickness Measurement

Complete construction of the linear actuator for probe life testing. Initiate life testing of several new eddy current probe designs.

Non-destructive TBC Evaluation

Fully evaluate the Sagnac interferometer for LUT inspections. Develop pass / reject criteria.

Technology Application

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

Section 2.2.5.2 (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 4Q98 through 3Q99

Electron-Beam High Thermal Gradient Tests

A) Flat tophat specimens (bare)

The flat tophat specimen was designed to simulate the thermal and mechanical stress conditions in the TBC near critical "high-C" region of the ATS stage one nozzle. No TBC damage was observed and no systematic decrease in TBC mechanical properties was measured following testing for 100 hours, 2500 cycles at full ATS conditions. This was the case for unaged tophats as well as for tophats that were aged to 50% and 75% of expected ATS TBC life.

TBC degradation during this testing was evaluated by comparing the microstructure and compressive-shear failure strains between hot and cold regions of the tested tophats. No systematic difference in TBC horizontal cracking, bond coat oxide thickness or TBC residual strain to failure was observed between the hot and cold sections of the tophats. In addition, no systematic difference in TBC residual strain to failure was measured between tophats with different pre-test furnace aging.

B) Flat Tophat specimens (CMAS)

Two CMAS-coated flat tophats were tested under conditions which produced partial CMAS infiltration into the TBC. In the first test, no TBC spallation occurred after 87 two-minute cycles, although melting and infiltration of CMAS was confirmed by destructive evaluation. However, TBC spallation occurred in the second test after only 22 cycles. The electron beam power is controlled by the TBC surface temperature, as measured using an Infra-Red (IR) optical pyrometer. It is believed that the IR emissivity of the TBC changes considerably during CMAS infiltration, which may explain the difference in results between these two tophats.

C) Fillet Tophat specimens

One fillet tophat was tested under full ATS conditions for 2500 cycles. The sample was designed to simulate the thermal and mechanical stress conditions in the TBC near critical fillet region of the ATS stage one nozzle. The TBC was machined to produce a uniform thickness in the fillet region. No spalls or hot spots were observed during the testing; however, the TBC top surface ran hotter and the metal ran colder than expected due to the increased thermal resistance of the coating in the fillet.

Thermal conductivity measurements of the free-standing bond coat and top coat removed from this fillet tophat were performed. The thermal conductivity of both the bond coat and top coat were each approximately 25% lower than that of the same coatings applied to planar samples. The higher thermal resistance is caused by high coating porosity and poor splat-to-splat bonding, which are caused by geometric effects that adversely affect the spray process.

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

Develop transfer functions between TBC top coat microstructural variables, laser ultrasound signatures, mechanical properties, and thermal conductivity.

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 h/cycle) and dwell temperatures (1037-1148°C, 1900-2100°F), and incorporating the results into an existing cumulative damage model. Accelerated testing at temperatures below 1037°C (1900°F) will be accomplished using a tensile Thermal-Mechanical Fatigue test, which superimposes cyclic mechanical strain upon the cyclic thermal strain. In support of the modeling approach, microstructural features of the 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 due to variations in TBC microstructure, leading to design inaccuracy. Different methods of measuring thermal diffusivity and conductivity on flat and curved samples will be evaluated. The gas pressure dependence of thermal conductivity as a function of temperature will be measured. The results will be used to estimate the thermal conductivity of TBC at ATS conditions. The effect of thermal aging on TBC thermal conductivity will be quantified.

Progress 4Q98 through 3Q99

The relative contributions of time-dependent (oxidation) damage and cycle-dependent (fatigue) damage to ultimate failure of the TBC are being evaluated through mechanical tests 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.

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

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

Furnace Cycle Testing

Conventional ("porous") and advanced ("dense vertically cracked" or "DVC") TBC specimens were furnace cycled at 1148°C (2100°F) and 1093°C (2000°F) using dwell times of 0.1, 0.75, 10, and 20 hours per cycle. 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 mid-2000. To date, 21067, 9032 and 912 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 was fit using the cumulative damage model for the cases of parabolic and cyclic oxidation. In both cases a reasonable fit was obtained to the FCT data; however, the two curve fits yield markedly different estimates for the TBC spallation lives at low temperatures. Examination of the oxide growth kinetics at 1093°C (2000°F) indicated that a two-stage parabolic oxidation damage model is appropriate for 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 TBC coated superalloys.

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

Thermal Conductivity

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

A) Planar samples

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

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

B) Curved samples from parts

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

Plans for Next Quarter

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

Furnace Cycle Test

Test new samples at 1148°C (2100°F) and 1093°C (2000°F).

Continue testing at 1038°C (1900°F).

Thermal-Mechanical Fatigue Testing

Perform third TMF test at higher conditions. Evaluate samples using NDE and metallography.

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

Thermal Conductivity

Complete thermal conductivity measurements on samples from ATS Cascade nozzles, bucket and field-aged parts.

Determine 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 4Q98 through 3Q99

Cooling Air Cooling System

The 9H Cooling Air Cooling (CAC) skid was manufactured during 3Q99. This represented a significant milestone for the H program. The examination of the skid proved to be highly satisfactory, and the unit awaits shipment to the first 9H site. The successful fabrication of the 9H skid will provide valuable lessons learned for the 7H CAC skid. A 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.

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.

The steam valve design proceeded through its final design review stages, representing a culmination of two years work with GE's combined cycle engineering and the steam valve suppliers to produce a design that will meet the scheduling commitments to the first 9H site. This investment of thorough design engineering work will greatly assist in reducing the design cycle time for the 7H valves.

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. The third quarter saw the completion of the test plan for the 9H FSFL pre-shipment test and preparations for carrying out that test in early fourth quarter. The plan and the preparations required extensive collaboration with several different GE departments, including the test stand personnel, to develop a plan that will produce the needed data and provide a rigorous test of the new filtration equipment.

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 and is due for completion in the fourth quarter. The 7H diffuser will benefit from the design experience gained on the 9H diffuser.

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 fourth quarter will see the continuation of detail design work of the 7H. New members of the design team will be brought up to speed on the technical evolution of the unit, and lessons learned from the 9H system design and manufacture will be imparted to all members of the team. The development of 7H data blocks, which are critical for certain areas of the design to go to completion, will also be followed.

Steam Cooling System

The fourth quarter will be spent in focusing on completing the 9H design with the final design reviews, and then monitoring the valves through the procurement and fabrication stage.

The 7H design will then begin incorporating the lessons learned from the 9H, and modifying the design to suit the 7H's particular demands. The production of 7H data blocks also affects the design of the Steam Cooling System and their completion will be followed.

Clearance Control System

The immediate concern in the fourth quarter will be monitoring the 9H FSFL pre-shipment test. The results from this test will be examined to determine any required modifications to the current 9H design and how these results can be applied to the 7H design. Once the analysis of these results has been completed then detail design work on the 7H unit will proceed.

Exhaust System

The fourth quarter will see the completion of fabrication of the 9H diffuser. Completion of the manufacture will involve continuous work with GE's supplier, and most importantly, a test erection, tentatively scheduled for early first quarter 2000. The test fabrication is an extremely important step in the diffuser's development, since the diffuser's on-site installation represents a complex and critical step in the power plant's construction. The test fabrication will help eliminate many possible errors and ambiguities in the fabrication procedure. This test fabrication will be videotaped, and this tape will accompany the diffuser to the site to allow for further on-site guidance. The test fabrication, coupled with the actual on-site completion, will ensure a refined and efficient 7H procedure.

Technical Application

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

SECTION 2.3.2 (CCCL) CONTROLS

Objective

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

Progress 4Q98 through 3Q99

Control and protection strategies were developed and coded into the gas turbine and steam turbine control systems for the first combined cycle application. These algorithms have been module tested under simulation environment. Control equipment has been assembled in the controls engineering lab for testing combined cycle operational functions and dynamic characteristics. Control algorithms have been developed to support 9H FSFL pre-shipment test.

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, using actual control hardware. Control programs for the gas turbine and steam turbine will be installed into control panels. Verification of the control programs will begin. Expect to complete the second full-speed-no-load test. Field testing of the triple-redundant control system will continue with emphasis on operational reliability.

Technology Application

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

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

Objective

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

Progress 4Q98 through 3Q99

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

Reliability assessments of several accessories systems were performed using reliability block diagrams. These systems include: lube oil, seal oil, bearing lift oil, clearance control, atomizing air, cooled cooling air, and several balance of plant subsystems. Additional work was performed on reliability assessments for the steam cooling system and the fuel heating system.

FMEAs of the flange-to-flange components were provided to the current design engineers and teams to be reviewed and updated with the current design.

A component FMEA was completed on the spoolies and started on the bore tube.

A reliability and lifing assessment of the spoolie 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.

Reliability block diagrams for the gas turbine flange-to-flange, which includes scheduled maintenance intervals to replace/refurbish components, was completed. Analysis determine failure modes, where applicable, in order to identify the component and system expected failure rate.

Plans for Next Quarter

Continue steam cooling system assessment, including rotor steam delivery reliability, stator steam cooling circuit, and the overall steam cooling system.

Continue reliability modeling of the gas turbine flange-to-flange systems (compressor, combustion, turbine, and structures), 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.

Continue reliability assessments of several key systems, including; aft wheel shaft cooling system, lube oil system, and hydraulic system.

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 4Q98 through 3Q99

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 second 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 4Q98 through 3Q99

During the past year, manufacturing schedules were used to track status of assembly and delivery of components for the 9H gas turbine rebuild for the FSFL pre-shipment test and initial build of the 7H gas turbine. I-718 turbine rotor forgings were modified or replaced and assembled into a turbine rotor for the 9H FSFL pre-shipment test, and new forgings were machined for the 7H FSNL rotor. The 9H FSFL pre-shipment test rotor also included many steam system components for the rotor cooling system, which was not activated for the FSNL test last year.

TBC process qualifications for H-machine airfoil coating qualifications were completed for turbine buckets to support FSFL pre-shipment test.

The 7H gas turbine progressed to start of casing assembly and assembly of compressor and turbine rotors.

The test stand for FSNL testing of H design gas turbines was modified to support the FSFL pre-shipment test of the 9H and FSNL of the 7H in the 4th Quarter of 1999.

Plans for Next Quarter

During the next reporting period the 9H unit will complete FSFL pre-shipment testing, and the 7H unit will complete assembly and be moved to the test stand.

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 4Q98 through 3Q99

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 4Q98 through 3Q99

GEPS participated in the DOE-sponsored Advanced Turbine Systems Annual Review held on November 2-4, 1998 in Washington, D. C. The GEPS presentation reviewed the status of the ATS program, and provided a comprehensive overview of the component designs, rig testing, and 9H FSNL test program progress. GEPS also displayed views of the H machine in a photo exhibit.

GEPS completed negotiations with DOE/FETC on the Continuation Application for Budget Period 3 (1999).

The Budget Period 3 Program Plan was submitted to DOE/FETC. The Program Plan gives an update of the Program Schedule, planned testing, organization charts, and Statement of Work.

In September 1999, GEPS submitted a Continuation Application for Budget Period 4 (2000), which included actual costs through 2Q99, and estimated costs for the duration of the program.

A Program Review was held in 4Q98 in Schenectady, NY where highlights of the 9H FSNL testing and 9H/7H combustor design topics were discussed. The 1Q99 Program Review was held by videoconference, in which plans for Budget Period 3 testing milestones and schedules were presented. The 2Q99 Program Review was held at GEAE-Evendale, OH, to review the 7H compressor rig test plan and hardware assembly before the rig was shipped to the GEAE-Lynn, MA test facility. The 3Q99 Program Review was held in Schenectady, NY to review ATS program status, view preliminary 7H compressor rig test results, 9H/7H system combustor test development progress, and review the turbine rotor rig test plan, and tour the rotor rig test stand.

Plans for Next Quarter

GEPS will participate in the DOE-sponsored Advanced Turbine Systems Program Annual Review on November 8-10, 1999 in Pittsburgh, PA.

The Continuation Application submitted in 3Q99 will be negotiated 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 2.2.2.4.1 (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 2.2.3.5.1 (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 (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 2.2.3.5.9 (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 2.2.3.6 (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 will be performed to evaluate the long-term oxidation responses to this environment. Specimens will be subjected to steam exposure in an autoclave and removed at specified intervals for examination of oxidation characteristics.

Plans

This activity was completed in 4Q96.

Technology Application

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

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

Objective

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

Plans

This activity was completed in 4Q97.

Technology Application

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

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

Objective

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

Plans

This activity was completed in 1Q97.

Technology Application

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

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

Objective

Information to support selection of materials for the variable guide vane bushings and thrust washers will be gathered to ensure a robust and reliable design. Testing will be conducted to confirm materials selections, cover any parameters outside of existing data, and gather data for new materials.

Plans

This activity was completed in 2Q97.

Technology Application

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

Section 2.2.4.9 (GTMTSB) Structural Bolting

Objective

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

Plans

This activity was completed in 1Q98.

Technology Application

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

Section 2.2.4.11 (GTMTCB) Combustion Materials and Processes

Objective

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

Plans

This activity was completed in 4Q97.

Technology Application

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

Section 2.2.4.12 (GTMTST) Turbine Structures Materials and Processes

Objective

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

Plans

This activity was completed in 4Q97.

Technology Application

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

Section 2.2.4.13 (GTMTSH) Turbine Shells

Objective

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

Plans

This activity was completed in 4Q97.

Technology Application

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

Section 2.2.4.14 (GTMTSR) Seal Technology

Objective

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

Plans

This activity was completed in 4Q96.

Technology Application

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

Section 2.2.4.14.1 (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.