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**Utility Advanced Turbine Systems (ATS) Technology
Readiness Testing - Phase 3**

**Technical Progress Report
October 1 - December 31, 1997**

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ACRONYMS

ANSYS - finite element software	GEAE - GE Aircraft Engines
APS - air plasma spray	GEPG - GE Power Generation
CAD - computer-aided design	GEPS - GE Power Systems
CDC - compressor discharge case or casing	GTCC - gas turbine combined cycle
CDD - compressor discharge diffuser	HCF - high cycle fatigue
CFD - computational fluid dynamics	HIPed - hot isostatically pressed
CMAS - calcium magnesium aluminum silicon	HRSG - heat recovery steam generator
CMM - Coordinate Measuring Machine	HVOF - high velocity oxygen furnace
CNC - computerized numerical control	IGCC - integrated gasification combined cycle
CRD - GE Corporate Research and Development	IR - infrared
CSMP - Coordination through Short Motion Programming	IT - Inverse Time
CTP - critical-to-process	KCPs - key control parameter
CTQ - critical-to-quality	KNPs - key noise parameter
DFSS - design for six sigma	LCF - low cycle fatigue
DLN - dry low NOx	LCVT - liquid crystal video thermography
DOE - Design of Experiments	NDE - nondestructive evaluation
DOE - U.S. Department of Energy	NEPA - National Environmental Policy Act
DTC - design to cost	NPI - New Product Introduction
DVC - dense vertically cracked	P&ID - process and interface drawing
EA - Environmental Assessment	QFD - quality function deployment
EDM- electric discharge machining	RAM - reliability, availability, and maintainability
EDRs - electronic data releases	SSPM - steady state performance model
EIS - Environmental Impact Statement	SSRT - slow strain rate tensile
EPRI - Electric Power Research Institute	STP - Segment Time Programming
FEA - fluid element analysis	TBC - thermal barrier coating
FETC - Federal Energy Technology Center	TBO - time-between-outages
FMEA - failure modes effects analysis	TCP - Tool Center Point
FONSI - Finding of No Significant Impact	TDM - thermal dynamic model
FPQ - first piece qualification	TMF - thermomechanical fatigue
FSFL - full speed, full load	UAB - Utility Advisory Board
FSNL - full speed, no load	VGW - variable guide vane
	VSV - variable stator vane
	YFT - fluids analysis software

Section 1 Executive Summary

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

This report summarizes work accomplished in 4Q97. The most significant accomplishments are listed below:

9H/7H-common technology

- Completed the first TBC spray trial on a bucket replica in a production spray booth
- Performed the first flow check of production bucket airfoils
- Completed steam gland brush seal testing in a rotating rig
- Completed machining of all 9H turbine wheels
- Shipped the first set of 9H first- and second-stage nozzles to post-cast suppliers
- Completed 9H full speed, no load (FSNL) test plan
- Determined the required test sensors for the 9H FSNL test and the instrumentation drawings
- Installed the compressor blade strain gauges

7H-specific

- Established the 7H schedule and initiated the detailed 7H integrated design effort
- Initiated the 7H turbine rotor conceptual design effort
- Initiated the 7H compressor discharge case (CDC) conceptual design effort

Figure 1-1. Schematic of H machine cross section

Section 2 Technical Progress Reports

Section 2.1 (NE) NEPA

Objective

A draft topical report will be prepared which provides the environmental information associated with Phase 3, Technology Readiness Testing, as specified in the National Environmental Policy Act (NEPA). DOE will use this information to prepare the NEPA documentation for Phase 3. DOE will review the report and advise the participant of the acceptability of the report or the need for additional information. A final report will then be submitted.

A second draft topical report will be prepared which provides the environmental information associated with Phase 4, Pre-Commercial Demonstration, as specified in NEPA. DOE will use this information to prepare the NEPA documentation for Phase 4. DOE will review the report and advise the participant of the acceptability of the report or the need for additional information. A final report will then be submitted.

Progress for this Quarter

GE Power Systems received a Finding of No Significant Impact (FONSI) from DOE regarding the potential environmental, health, and safety impacts of the fabrication, assembly, and full speed, no load (FSNL) testing of the 7H in Greenville, SC. The FONSI was obtained as the result of GE's NEPA report, which was delivered to DOE in connection with the proposed ATS Phase 3R program.

In generating the FONSI, DOE has determined that GE is in compliance with all Federal, State, and local laws and regulations relating to the topics evaluated in the Environmental Assessment (EA), and that preparation of an Environmental Impact Statement (EIS) is not required.

With GE's assistance, DOE used the NEPA document to prepare an EA for the Greenville, SC, site. The EA evaluated impacts on the following: air quality, noise, biological and environmentally sensitive resources, human health and safety, esthetics and visual quality, water resources and water quality, soils and geology, cultural resources, recreational resources, land use, socioeconomic resources, environmental justice, infrastructure, and solid and hazardous waste management.

Plans for Next Quarter

This task has been completed.

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 (GT) Gas Turbine Design

Section 2.2.1 (GTAD) Aerodynamic Design

Objective

To achieve ATS performance goals, a four-stage turbine will be designed. Advanced aerodynamic technology (sometimes called 3D aerodynamics) pioneered at GE Aircraft Engines (GEAE) will be 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 for Next Quarter

This task has been completed.

Technology Application

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

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 lower cost and greater durability by applying proven GE Power Generation (GEPG) heavy-duty use design practices. The designs will be based on the GEAE GE Aircraft Engines CF6-80C2 compressor. Transient and steady-state thermomechanical stress analyses 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 tests (FSNL) of the first unit.

Progress for this Quarter

Component analysis for the 9H is complete, and all parts lives are calculated to meet product life requirements. Additional lifing based on GEPG product-line lessons learned from the GE Gas Turbine product line are being examined.

With the exception of a few blade stages, the manufacture and first piece qualification (FPQ) for all compressor parts—including compressor rotors, blades, through-bolts, and spacers—were completed at the vendor facilities. These components are now in various assembly stages at the GE Greenville facility, and completion for all compressor rotor assembly is scheduled for the end of February 1998, with stator blades being loaded through mid-March. The rescheduling of the variable stator vane (VSV) system in order to examine a higher

flow/power setting during FSNL testing is progressing with the sourcing of additional torque shafts and third- and fourth-stage turnbuckle links for the production design. The post-test data reduction is from the Rig 2 tests for rotor thermals, and final aerodynamic performance and aeromechanics issues led to the conclusion that this VSV rescheduling had the potential for significant performance benefit if blade aeromechanics are acceptable for the new setting.

Additional instrumentation (light probes) for aeromechanics has been added to the inlet and compressor case sections of the casings. The compressor discharge casing (CDC) and inner barrel completed FPQ and arrived in Greenville for assembly operations. The first half-set of the compressor discharge diffuser (CDD) also passed FPQ and is in assembly. Casting difficulties of the CDD necessitated the decision to accept the second half-set as "test only," and additional low-cycle-fatigue/high-cycle-fatigue (LCF/HCF) testing along with sourcing a backup half-set has been initiated for the production unit.

The 7H preliminary aerodynamic design for the new airfoil stages 0, 1, 2, 14, 15, 16, and 17 was completed. Initial aeromechanical evaluation of the airfoils is complete and acceptable. An initial compressor flowpath incorporating lessons-learned on 9H and product unit issues is now being frozen. Initial stress analysis of forward-stage blade dovetails was completed before the flowpath was set.

Plans for Next Quarter

With the completion of 9H hardware components, work for the 9H program will focus on final assembly drawings for initial machine testing, and providing engineering support for assembly and testing preparation of the 9H compressor. 9H compressor assembly including instrumentation will be completed in 1Q98, and unit assembly will be nearing completion by the end of 1Q98.

The 7H design work will accelerate with release of components needed for sub-scale testing. Product definition will begin with initial life and product specification calculations. Detailed product definition and trade studies to define the basic geometry will begin with major compressor components.

Technology Application

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

Section 2.2.2.2 (GTFFCB) Combustor Design

Objective

The objective of this task is to design a combustor based on the commercial DLN2 combustion system, with modifications made for improved use of available air, reduced cooling, and greater load turndown capability. This design will be similar for both the 7H and 9H machines. It will be configured to ensure the ability to use preheated fuel. Rig testing of full-scale and scaled components will be conducted at 7H and 9H cycle conditions. The final configuration will be validated in single-combustor, full-scale tests under full operating conditions.

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

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

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

Progress for this Quarter

Production of the transition piece assemblies continued. All transition piece bodies and aft frames were cast and installation of aft frame cooling holes began. The first phase of thermal barrier coating development was completed and a decision was made to continue development into a second phase to further define process parameters.

Endcover and swizzle thermal and stress analyses continued, and a preliminary strategy to obtain the design cyclic life of the endcover without internal material cracking was adopted.

Shakedown testing was conducted in the full-condition GE Aircraft Engines (GEAE) Stand A2 in preparation for full stand qualification in 1Q98.

A method for generation of smooth 7H transition piece body shapes in semi-automatic fashion using standard CAD software advanced significantly. This methodology will be used to generate a family of transition piece shapes in Design of Experiments (DOE) fashion to optimize transition piece design. In addition, the interface with the compressor discharge case (CDC) design was analyzed for combustion system access and removability.

Plans for Next Quarter

GEAE Stand A2 will be fully qualified and swizzle-based combustion system development testing will be well underway. The endcover analysis will be close to completion, and the family of 7H transition piece body shapes will be close to definition.

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 for this Quarter

The preliminary transient thermomechanical turbine rotor structural system model is currently being exercised to complete the 9H secondary flow system. Several startup-to-steady-state analyses are complete, including a shutdown analysis. Multiple variations on secondary flow parameters were analyzed. The critical dimensions drawing is in the manufacturing review cycle.

Plans for Next Quarter

The 9H secondary flow system will be completed. Construction of the final turbine rotor structural system model will begin. The critical dimensions drawing will be released to initiate tooling development.

Technology Application

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

Section 2.2.2.3.1 (GTFFTR) Turbine Rotor Mechanical Analysis

Objective

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

Progress for this Quarter

A complex 3D ANSYS stress model of the bucket steam supply manifold was built. The model incorporated internal geometry, non-constant wall thickness, and fillets. Analyses were performed for speed and pressure loadings. Some investigations were made into the effect of reducing the spacer rabbet length, which would lead to less support for the manifold. As more data became available on interacting components, boundary conditions were enhanced. The next steps are to do a full analysis incorporating the 1-2 spacer to thoroughly study the interaction between the components, and to add in the thermal loading effects.

The automation of the GE Power System (GEPS) lifing procedures applied to the ATS gas turbine included several significant steps. The first step was accurate calculation of mechanical and thermal stress concentration factors (K_t) for rotors and spacers at various critical locations. The 3D stress state was then obtained for all rotors and spacers using these K_t 's. An independent Fortran program was written to use these stresses and apply the GEPS lifing methodologies to compute LCF life numbers for ATS rotors and spacers. The LCF life was obtained at various critical locations on all rotors and spacers for 3600 rpm (7H speed). These life numbers are now being used to modify the existing design to meet 7H requirements.

The parametric optimization of the 7H gas turbine second-stage wheel is in progress. The modeling and meshing of the 2D geometry has been completed. Approximately 100 geometry and loading configurations will be evaluated to identify the best possible design.

Plans for Next Quarter

Mechanical and thermal design and analysis support for rotor components will be provided as needed. Design reviews will be written documenting results.

Technology Application

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

Section 2.2.2.3.2 (GTFFTR) Wheel Forging Residual Stress Analysis

Objective

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

Progress for this Quarter

A thermal stress analysis simulating the quenching process of the 7H second-stage wheel was completed. Peak radial and hoop stress levels were similar to those seen in the 7F first-stage wheel.

A thermal stress analysis simulating the aging process of the 7H second-stage wheel was also completed. Peak radial and hoop stress levels were higher than those seen in the 7F first-stage wheel.

In the 7F first-stage wheel, residual growth was underpredicted by a factor of two when residual stresses were ignored. The stress and strain results from the 7H second-stage analysis

are being used as bounds for performing creep tests on the IN718 material (ATS second stage).

Stress relaxation experiments were performed on the IN706 material and indicated that little relaxation occurs during the aging process. For this reason the simulation of the machining and subsequent overspeed pre-spin of the 7F first-stage wheel was performed using the plastic strain results at the end of the aging process, ignoring any creep strain that may have developed.

Simulations of the machining and subsequent overspeed pre-spin of the 7F first-stage wheel were completed. Plastic strains at the end of the aging process were mapped onto the machined shape using the GE Aircraft Engines (GEAE) code Siesta, and subsequent plasticity analyses of the pre-spin were performed using SUSAN. The results are encouraging. The new analysis procedure, which includes residual stress from the quenching and aging process, predicts a residual radial growth close to that obtained experimentally.

Plans for Next Quarter

The current analysis procedure using SUSAN requires the use of a bilinear stress-strain curve after mapping the plastic strains. The selection of the yield stress and hardening modulus will require some additional analysis. The approach will be validated by using an alternate analysis procedure in which the machining step is explicitly modeled. GEAE is modifying the SUSAN code to allow the use of a multilinear kinematic hardening model.

Technology Application

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

Section 2.2.2.3.3 (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.

Progress for this Quarter

The CFD analysis of the steam circuit rotor return bore tube was completed. The loss coefficient is very close to the value predicted by the modified 1D approximation employed in the overall YFT circuit model. Rotational effects were controlled well by the guide vanes at the inlet to the return bore tube.

CFD runs of the baseline supply and return bucket manifold concepts were performed. Results show adequate flow distribution into first- and second-stage buckets. The hydraulic performance of the supply manifold based on CFD results matched the 1D estimates in the overall system analysis.

Pressure drop analyses of the return manifold, however, indicated relatively high pressure loss. The pressure drop of the steam distribution system plays a significant role in the performance of the machine. Design modifications based on observed flow patterns were incorporated into the design, and additional CFD analyses were performed.

Two new geometries were run. The results of the first case indicated a significant improvement over the original concept that may result in pressure drop savings in the return manifold of up to 50%. The second geometry, based on the CFD results of the first case, attempted to further streamline the flow as it entered the axial tube. Results of this run are anticipated in 1Q98. Flow distribution into the buckets was only minimally affected by the design modifications introduced.

Plans for Next quarter

Further improvements on the manifold hydraulic performance will be sought. As static test data for the supply manifold become available, comparison and assessment of the analytical models may be performed.

Technology Application

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

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

Objective

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

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

Plans for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.2.3.5 (GTFFTB) Bucket Temperature Monitoring

Objective

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

Progress for this Quarter

The pyrometer installed on an F-class gas turbine continues to provide bucket temperature data that will be used to establish design criteria and operability of the system on the ATS gas turbine.

Plans for Next Quarter

Pyrometer data from the test site will be analyzed for stability and trends. Additional tests will be performed to explain the drift observed in the data. Tests will also be performed on TBC-coated parts.

Technology Application

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

Several other technologies were investigated, such as tracer leaks, vibrational signatures, steam pressures, and steam flowrates, but they were discarded in favor of monitoring the bucket temperatures using pyrometers attached to the outer casing of the turbine with a direct line-of-sight view of the first- and second-stage buckets. Pyrometers have several significant advantages: (1) they respond to the parameter of the buckets that is of most concern, i.e. the temperatures; (2) all the buckets in a stage come into the field of view of a single fixed pyrometer; and (3) the detection system has a rapid response time.

Section 2.2.2.4 (GTFFTB) Turbine Bucket Design

Objective

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

can deal with anisotropy), and corrosion/oxidation analysis will apply throughout. Drawings and specifications will be developed in preparation for manufacturing.

Progress for this Quarter

Detail design of the 9H buckets continued. The first complete set of castings for all four stages was shipped from the casting vendor. Post-cast operations were initiated on all stages. Detailed transient analysis continued on the steam-cooled buckets. As part of a GE quality effort called "design for six sigma" (DFSS), robust design activities were initiated on steam-cooled buckets in order to optimize casting tolerances for maximum yield with minimum life impact. Design improvements were initiated for incorporation in the next set of hardware based on results of the first casting campaign. Component bench testing was initiated to confirm frequency margins.

Detail design of the 7H continued. Resources dedicated to the 7H were significantly increased. Changes to the flowpath were initiated to enhance performance and reduce machine costs. Detailed reviews were held with core manufacturers and casting vendors to establish agreement on core features.

Plans for Next Quarter

Detailed analysis of the 7H buckets will continue with a goal of electronic data releases (EDRs) in 2Q98.

Detail design of the 9H will continue with further transient analysis, and design modifications for enhanced producibility. The finished buckets for the first machine will be delivered to Greenville and installed in the rotor. Component bench testing will be completed.

Technology Application

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

Section 2.2.2.4.1 (GTFFTB) S1B and S2B Wheel Dovetail Analysis

Objective

The objective of this task is 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 for Next Quarter

This task has been completed.

Technology Application

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 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 is to optimize stresses and creep deflections in the ATS third- and fourth-stage bucket shrouds. Detailed 3D creep analyses are needed to ensure that the stresses are within the required limits for creep life.

Plans for Next Quarter

This task has been completed.

Technology Application

The analysis performed here will be 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 is 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 can be shown to be non-critical, bucket yield can be improved.

Plans for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.2.4.3.1 (GTFFTB) Bucket Robust Design and Life Assessment

Objective

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

Progress for this Quarter

The robust design and life assessment of the full speed, no load (FSNL) 9H first- and second-stage buckets are complete. Successful real time lifing of castings enabled on-time shipment of the castings. Modifications to the bucket geometries, particularly wall thicknesses in the root fillet and shank regions, led to designs that will meet 400-cycle life and, eventually, full life requirements.

Plans for Next Quarter

Validation of the 400-cycle life results and full life designs will be performed. The robust design and life assessment methods applied to the 9H buckets will be applied to the 7H buckets.

Technology Application

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

Section 2.2.2.4.4 (GTETIH) Bucket Tip Treatment Heat Transfer

Objective

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

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

Progress for this Quarter

All flow and heat transfer tests scheduled for 1997 were completed. Airfoil static pressure distributions were obtained at both the mid-span location of the cascade and near the tip, without a tip clearance, to check Mach number profile against design intent. The near-tip airfoil pressure distribution was then measured with the presence of a tip clearance gap. The resulting Mach number distribution gives a good differential pressure driving force distribution for tip leakage and heat transfer. The heat transfer airfoil with etched thin-film tip heater and liquid crystal layer was then installed and tested to determine both plain tip and rub-strip geometry heat transfer distributions at the engine design Reynolds number. In these tests, the tip perimeter was formed by a sharp edge. Tests for both cases were repeated with very good agreement of results. The rub-strip geometry was found to have an overall higher heat transfer on the blade tip by about 15%. Inlet freestream turbulence intensity was measured as approximately 4.5%. Further tests were conducted to measure the shroud surface pressure field opposite the blade tip area for each of the two tip geometries. These measurements indicate that the rub-strip geometry does reduce the tip leakage flow somewhat. Test data were reported to GE Power Systems (GEPS) design engineers.

Plans for Next Quarter

The blade tip cascade will be used to obtain a more complete knowledge of the present tip geometries and the associated heat transfer and leakage, as well as to test alternate geometries and effects of deteriorated conditions. Specifically, the pressure field on the blade tip will be measured to quantify leakage paths. The inlet turbulence intensity will be measured again to confirm previous results, and some attempt may be made to increase this intensity. Heat transfer will be determined for at least one alternate rub-strip geometry, as well as for one reduced tip clearance gap case. The effect of tip rubs on heat transfer and leakage will also be determined.

Technology Application

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

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

Objective

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

Plans for Next Quarter

This task has been completed.

Technology Application

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

Progress for this Quarter

No activity took place on this task during 4Q97.

Plans for Next Quarter

Cascade slave hardware will be completed and shipped to NASA in preparation for 2Q98 test.

Technology Application

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

Section 2.2.2.5 (GTFFTS) Turbine Stator Design

Objective

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

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

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

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

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

Progress for this Quarter

A 3D transient analysis was completed on the outer turbine shell. Several different transients were run to determine the casing transient stresses and casing deflections and casing out-of-round. A detailed 3D shell system model of the inner and outer shells and mounting pins was

completed to determine the loading on the pins supporting the inner shell within the outer shell that results from distortion of the inner and outer shells during transient operation. Further transient analyses of the inner shell were completed to determine transient tip clearances and inner shell stresses and out-of-round. A transient analysis of the first-stage nozzle and shroud was completed and is currently being analyzed to determine transient stresses. The flowpath for the 7H turbine was defined.

Plans for Next Quarter

A 3D creep analysis of the second-stage nozzle will be completed. Further transient analyses of the inner and outer shells, as well as the inner and outer shell system model, will be completed. Further detailed 3D analysis of critical areas of the steam-cooled components will be performed. Detailed aerodynamic definition of the 7H components will be completed through iteration of the airfoil shapes between the aerodynamic and mechanical design groups. Trade studies will be completed to define the airfoil cooling configurations, and secondary flow studies will be performed to determine the overall turbine flow circuit design. An initial turbine cross section will be developed and major interfaces defined.

Technology Application

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

Section 2.2.2.5.1 (GTFFTS) Turbine Stator Robust Design

Objective

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

A "robust design" is a design that satisfies the product performance requirements in an optimal manner and also exhibits minimal sensitivity to variabilities arising from various sources, such as manufacturing processes and tolerances, material behavior, operating environment, in-service damage, and maintenance and repairs. The methodology consists of the following key steps: (1) identification of critical-to-quality (CTQ) characteristics, key control parameters (KCPs), and key noise parameters (KNPs); (2) definition of the Design of Experiment (DOE) matrices for KCPs and KNPs; (3) execution of the DOE matrices through analysis, testing, prototyping, and/or manufacturing; (4) statistical analysis of the DOE 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.

Progress for this Quarter

First-Stage Nozzle

Updating of the finite element model for the first-stage nozzle model is nearly complete. The remainder of the work required to continue the robust design will be carried out by the designers. The development of the response-surface-based spreadsheet tool was completed and transitioned to the designers for use on the first-stage nozzle.

A GE quality effort called "design for six sigma" (DFSS) was applied in several other areas including response surfaces for system-level trade-off studies between low cycle fatigue (LCF) life and combined-cycle efficiency and for steam-cooled joint design between the outer sidewall and cover.

Second-Stage Nozzle

Consultation on applying DFSS quality tools to the second-stage nozzle was provided.

First-Stage Shroud

A second-phase design of experiments (DOE) was executed on the first-stage shroud. Results were analyzed to determine the sensitivity of various parameters, KCPs as well as KNP's, to LCF life.

Rotor Components

Consultation on applying DFSS quality tools for the robust design of several rotor components: spoolies, main steam tube, and manifold was provided. During this period attention was focused on defining benefits resulting from these projects and documenting best practices and lessons learned.

Plans for Next Quarter

First-Stage Nozzle

Best practices and lessons learned will be documented, and the scope of the follow-on plan to complete the application of robust design to the first-stage nozzle of the ATS gas turbine will be determined.

Second-Stage Nozzle

Consultation on applying DFSS quality tools will be provided as needed by the GE Power Systems (GEPS) staff for full-life, low-cost part design.

First-Stage Shroud

Best practices and lessons learned will be documented, and the scope of continuing efforts will be determined.

Rotor Flanges Design

Best practices and lessons learned will be documented and the scope of the follow-on efforts will be defined.

Technology Application

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

Section 2.2.2.6 (GTFFST) Structures Design

Objective

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

Progress for this Quarter

Exhaust Frame and Diffuser

The exhaust frame and diffuser supplier completed machining and assembly to produce the first exhaust frame. Because the forward diffuser is inaccessible after final assembly into the frame, GE Instrumentation personnel went to the vendor and installed the instrumentation in the forward diffuser. The aft diffuser duct completed performance tests and showed promising results (for minimal loss on pressure recovery) at CRD. An additional acoustic resonance concern arose in post-test data reduction that showed a need for further research at low swirl turbine exit flow at low and part power. The aft diffuser inner barrel fabrication and machining drawing was issued and sent to the vendor for production.

Steam Gland

The delivery of the steam gland is on schedule to the 9H FSNL test pending completion of final machining and seal manufacture. The vendor completed the machining for the first unit, and final pipe attachment welding is in process. The steam gland will be hydrostatically tested and shipped to Greenville in 1Q98.

#2 Bearing Housing

The bearing housing was completed at the machining vendor site and passed first piece qualification (FPQ). This housing has been shipped from the vendor and is expected to arrive in Greenville on January 18. Transient thermal (machine trip) and flow analysis work is continuing on the heat rejection at the bearing resulting from steam supply through the rotor

bore. A detailed deflection and thermal analysis of the bearing seals and journal surface for steady-state and normal shutdown conditions with machine trip and blackout conditions is in process. Standard bearing instrumentation (for radial rotor vibration, bearing pad thermocouples, and stator vibration sensors) and the prototype instrumentation assembly drawings were completed.

Plans for Next Quarter

Exhaust Frame and Diffuser

The exhaust frame flow test will be held in the Greenville test facility. This test is to validate the expected leakage at each of the sealing locations and provide final feedback to orifice sizing in the supply manifolds. The exhaust frame will then be sent to the stator tube assembly area for unit assembly.

Steam Gland

The vendor will complete the machining FPQ, and the steam gland will be shipped to Greenville assembly. The steam gland design will be examined for possible cost reduction/design optimization using brush seals in place of the labyrinth seals for the first 7H unit.

#2 Bearing Housing

The bearing housing will be aligned and installed in the 9H unit assembly. All interfacing conditions with the rotor, bearings, etc., will be established for off-design conditions (e.g., power turndown and machine trip). Any special requirements for safe soakback thermals in the journal bearing area will be designed and released. The 7H application will be examined for oil flow requirement and the lack of capability to increase the oil flow passage sizes.

Technology Application

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

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 are to test potential ATS gas turbine exhaust diffuser geometries for pressure recovery performance and to verify that the design selected does not excite acoustic resonances.

The test program includes 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 will require axial ribs in the walls of the diffuser flowpath. Impact on pressure recovery will be measured. Several other tests will be performed, each with the aim of maximizing performance. These tests include 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 will be tested to verify that no acoustic resonances are excited, particularly at full speed, no load (FSNL) conditions.

Progress for this Quarter

Acoustic testing of the 1/13.2-scale flow model of the ATS gas turbine exhaust system was completed. Final analyses of the pressure recovery and acoustics results were completed and transmitted to the exhaust system design team.

Plans for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.2.6.2 (GTFFST) Steam Box CFD Analysis

Objective

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

Plans for Next Quarter

This task has been completed.

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 serves three purposes: it incorporates rotational effects and confirms the 1D analyses of the YFT study of the steam distribution system; it points 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 will be designed to be aligned with the incoming steam.

Section 2.2.2.7 (GTFFMS) Mechanical System Design

Objective

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

Progress for this Quarter

The focus of work in this reporting period was on 9H detail design and supporting technology development that benefits both the 9H and 7H turbines. Performance estimations were updated to reflect the current component designs. Engineering milestone and manufacturing schedules were updated, reflecting the current cycles and customer requirements.

7H system level studies continued to be performed to optimize cost, performance, weight, size, maintainability, reliability, and manufacturability. Performance, cost, weight, and other system level and integration issues were monitored and tracked. The systems review team, which includes engineering, manufacturing, sourcing, and maintainability personnel, continued to meet to review the merit of system issues and determine whether incorporation of ideas meets system goals such as cost, schedule, and performance.

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

The 9H mechanical interfaces were confirmed and updated. Reviews were conducted for the current 9H and 7H NPI tollgates, with the focus on completion in 1Q98. An assembly review of the H test stand was conducted at the GE gas turbine manufacturing facility in Greenville, SC, to ensure readiness for full speed, no load (FSNL) testing.

Plans for Next Quarter

An integrated engineering and manufacturing 7H schedule will be completed and implemented in the H NPI organization. The 7H design to cost (DTC) and performance models will be updated to include the latest configurations. The 9H first unit assembly will continue, nearing completion in preparation for the FSNL test planned for 2Q98. Engineering work effort will shift to focus on the 7H. A meeting of the Utility Advisory Board will be held to update the U.S. utilities on the progress of the GE H gas turbine. The cross-section drawings will be updated for both machines.

Technology Application

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

Section 2.2.2.7.1 (GTFFMS) Transient Gas Turbine Cycle Model

Objective

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

Progress for this Quarter

Effort in 4Q97 was largely directed toward remodeling the overall combined cycle plant to bring it up to current design status and make it consistent with the gas turbine model outputs. Equipment and auxiliary systems and the control were updated to reflect configuration and application changes that have occurred since the original model was put in place. The resultant modeling changes required more debugging effort than expected; in addition, it also proved necessary to debug the transient cycle deck when it operated in solution regimes that were not originally anticipated. Integration of the rotor heat soak code into the model was begun.

Work was performed on several areas of the modeling code to reduce calculation time, which is critical for transient simulations. A code profiler indicated that the gas properties evaluations require a large percentage of CPU time. The gas properties have been revamped, and the profiler indicates that computation time will be reduced by half. The profiler also indicated that the steam property evaluations for steam cooling are large consumers of CPU time; the faster steam property modeling package available with PC-Trax is now being used.

Plans for Next Quarter

Comparison of the heat soak model to more detailed analyses will be completed, and the model will be integrated into the ATS gas turbine transient model. The stress model will be developed and added to the heat soak model. The gas turbine cycle model will be updated to represent current status performance levels. The faster gas property evaluation package will be integrated into the model.

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 failure modes effects analysis (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 CCST plant transient model runs on a PC with the OS2 Operating system using the PC-Trax program.

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

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

Objective

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

Progress for this Quarter

The 9H turbine base was received from the supplier as built from the released drawings. No technical issues were found.

Final Design Reviews were held for the following piping systems: Air Extraction, Exhaust Frame Cooling Air, Clearance Control, Second-Stage Nozzle Cooling, and Cooling-Air Cooling. All design drawings related to these piping systems were released. Design activity will continue toward completing the balance of piping systems and releasing build documentation.

Plans for Next Quarter

System requirements will continue to be addressed and reviewed. Work on final piping designs will continue. Present plans are to release completed build documentation for the Cooling and Sealing Air system.

Technology Application

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

Section 2.2.2.9 (GTFFIT) Instrumentation and Test

Objective

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

Progress for this Quarter

The full speed, no load (FSNL) test plan and instrumentation Design Review was held on December 12, 1997. The required test sensors for FSNL are complete. The compressor instrumentation drawings are complete. The compressor blade strain gauges are installed.

Plans for Next Quarter

The number of sensors required for the flange-to-flange gas turbine unit and power plant components for full speed, full load (FSFL) tests will be established. The FSNL test plan will be revised to accommodate the Design Review concerns and comments. The turbine instrumentation drawings and telemetry system design will continue. The compressor rotor and blade instrumentation for the FSNL test will be completed.

Technology Application

These are test plans to establish the instrumentation requirements for 7H and 9H FSNL and FSFL tests.

Section 2.2.3 (GTET) Technology Validation

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

Section 2.2.3.1 (GTETNC) SIN Design

Section 2.2.3.1.1 (GTETNC) Nozzle Cascade CFD Analysis

Objective

The objective of this task is to apply a fully viscous 3D computational fluid dynamics (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 becomes the vehicle to apply the Nozzle Cascade Test data to the actual machine design problem.

Plans for Next Quarter

This task has been completed.

Technology Application

The validation of NOVAK3D predictive capabilities provides a valuable tool to evaluate the impact of design modifications and off-design performance of ATS nozzles in particular. It also contributes to a more realistic calculation of heat transfer coefficients and consequently enhances 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 is 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 for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.3.2 (GTETRS) Rotor Steam Transfer

Objective

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

Progress for this Quarter

When the steam first comes on board the rotor, it travels down an axial tubular annulus before being split into eight separate passages that flow steam radially. Since analysis indicated that this axial flow swirls, a flow test was set up and run to investigate the flow pressure loss resulting from this swirling flow being split and turned radially. Test results were compared with analytical predictions.

A flow rig was constructed for a steam supply manifold that is used to distribute steam to the buckets. This test will characterize the flow losses in the manifolds and help validate the analytical models that will also model the rotational effects on the steam flows.

Plans for Next Quarter

The supply steam manifold test will be completed and the results compared with analytical results. In addition, the flow rig will be modified to accept a return steam manifold model, so that a test can be run when the manifold design is completed.

Technology Application

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

Section 2.2.3.3 (GTETSE) Rotor-Bucket Steam Transfer Spoolie

Objective

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

Progress for this Quarter

Several tests of larger spoolies were run on a new test rig at simulated engine operating conditions of temperature, pressure, G-field, and environment (steam).

Preliminary testing in steam successfully demonstrated that the spoolie wear rates with the largest spoolies are consistent with the previous, successful small spoolie results. A minimal interference test specimen was prepared, but testing has been delayed because of problems with an alternative coating.

The rig has since been modified to cycle side loading to test for fatigue in addition to leakage endurance.

A rig was constructed to investigate the endurance capability of the spoolie coating to small movements between the components that are experienced when the rotor is on turning gear, when there is no rotational G force to rigidly lock the components in position. This low rpm rotational rig has run, verifying lock-up rotational speeds and a baseline steady leakage rate.

Plans for Next Quarter

A wear coating coupon test matrix is being developed to investigate the influence of various coating manufacturing parameters on wear rate, to optimize wear, leakage, and durability in a steam environment. The testing is planned to begin early in 1Q98.

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

Technology Application

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

Section 2.2.3.4 (GTETRH) Rotational Heat Transfer

Section 2.2.3.4.1 (GTETRH) Rotational Effects on Bucket Mixing Ribs

Objective

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

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

Progress for this Quarter

The mixing ribs installed in the turbulated test duct in the full-scale test rig have been evaluated over the buoyancy number range of interest at Reynolds numbers up to 1.3×10^5 . The data taken to-date confirm the benefit of using mixing ribs at high buoyancy numbers and also show that the specific radial location of the ribs has a significant effect on the lead and trail side heat transfer.

Plans for Next Quarter

The data acquisition above Reynolds numbers of 1.3×10^5 will be completed. Using the results obtained in the full-scale test rig, an additional task will be performed that will evaluate the effect of various radial locations of the ribs in the low-cost, small-scale test rig. The final report will be written.

Technology Application

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

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

Objective

The objective of this task is to determine the effect of rotation on the pressure drop in a radial bucket cooling passage. The computational fluid dynamics (CFD) computations of the effect of rotation on bucket cooling passage heat transfer and pressure drop indicate 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 for Next Quarter

This task has been completed.

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 (GTETIH) Surface Enhanced Internal Heat Transfer

Section 2.2.3.5.1 (GTETS2NHT) S2N Trailing Edge Flow Test

Objective

The objective of this task is 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 is 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 keeps the important geometric variables of the passage close to the actual design. It has 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 for Next Quarter

This task has been completed.

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 allows the design to obtain the desired heat transfer enhancement for the passages and to channel the cooling flow near the apex of the triangular flow passage near the trailing edge region effectively.

Section 2.2.3.5.2 (GTETIH) S2B Trailing Edge Heat Transfer Tests

Objective

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

Progress for this Quarter

Experiments were conducted to determine the effect of rotation on heat transfer in ducts of narrow cross section (length-to-width ratio of 10:1), oriented parallel to, and at a 45° angle to, the axis of rotation. In the experiments, a high-molecular-weight gas (Refrigerant-134A) at ambient pressure and temperature conditions was used to match the dimensionless parameters at engine conditions. Thin-foil heaters were used to produce a constant heat flux at the long sides of the duct; the narrow sides were unheated. An existing rotating rig was used for the testing. The rotating disk was modified for use with the test ducts.

Testing of the 45° configuration was completed. Correction of the test results for heat loss and thermocouple error is underway.

Plans for Next Quarter

At present there are no plans to continue this work into 1Q98.

Technology Application

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

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

Objective

The objective of this task is 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 will be compared with the design calculations and expectations. A test rig is used to simulate the design impingement jet plate geometry as closely as possible. The test section walls are 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 are then converted into heat transfer coefficient values.

Plans for Next Quarter

This task has been completed.

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 is 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 for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.3.5.5 (GTETIH) Bucket Tip Closed Circuit Cooling

Objective

The objective of this task is 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 for Next Quarter

This task has been completed.

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 is 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 for Next Quarter

This task has been completed.

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

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

Plans for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.3.5.8 (GTETIH) S1N Trailing Edge Heat Transfer Tests

Objective

The first-stage nozzle trailing edge triangular cavity is air cooled and uses a combination of several cooling techniques. The turbulated main passage feeds several trailing edge slots whose heat transfer is enhanced by pin fins and high-solidity turbulators. The root region includes a 180° turn that feeds three trailing edge cooling slots. The flow and heat transfer inputs for the design are complex and need verification testing.

The objective of the task is to build a representative model of the trailing edge cavity and measure the local heat transfer coefficients to ensure that (1) the heat transfer coefficient correlations used in the design are appropriate and (2) there are no flow recirculation or uneven distribution regions where the heat transfer coefficients are lower than the expected values.

Plans for Next Quarter

This task has been completed.

Technology Application

The flow and heat transfer results obtained will verify the design tool predictions and ensure that the predictions are correct and that there are no regions that have friction and heat transfer coefficient values different from the design assumptions.

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

Objective

The objective of this task is to investigate and determine the heat transfer coefficient enhancements possible in the first-stage nozzle. Internal cooling will be 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 will concentrate 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 will supply data and correlations to be used for advanced machine design conditions. Heat transfer and pressure drop data are required at far higher Reynolds numbers than previously tested with common turbulator geometries and passage aspect ratios.

Plans for Next Quarter

This task has been completed.

Technology Application

The results from this task are applicable to any non-rotating components in the ATS gas turbine that use turbulated passages for cooling. As long as rotational effects are accounted for, these results are 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 is to understand the physical phenomenon that causes the observed difference. The local static pressure distributions along the cross flow regions of the impinging jets will be measured for two inlet boundary conditions, one with a wall and the other with a constant pressure. Tests will also be conducted with the cross flow discharging in one direction across the impingement jets and discharging in two directions symmetrically from the center row.

Plans for Next Quarter

This task has been completed

Technology Application

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

Section 2.2.3.5.11 (GTETIH) Production Airfoil Flow Checks

Objective

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

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

Progress for this Quarter

Flow tests were initiated with a cast second-stage bucket and four of the impingement inserts of the first-stage nozzle cooling circuits.

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 jet supply flow areas. The first step was pin-checking each jet hole diameter. Next the overall flowrates with all the impingement holes active were measured for three supply-to-discharge pressure ratios. The last step was measuring the static pressure distributions at the various impingement jet supply rows at selected locations along the impingement insert to check the uniformity of the supply pressure, which will be a measure of (1) the uniformity of the flow and (2) the impingement heat transfer distributions among the various rows of impingement jets. The flow tests for impingement inserts for cavities 3 and 4 were completed. The results showed that the average pin-checked jet diameters were slightly larger than the design requirement. These larger jet diameters resulted in a higher flowrate than the calculated values for a given supply-to-discharge pressure ratio. The static pressure distributions at the various jet row locations were found to be uniform. Inserts 1 and 2 will be tested early in 1Q98.

To provide a proper baseline comparison, the YFT model of the second-stage bucket was obtained and modified to reflect differences between the bucket in service and the bucket in the flow tests. Those modifications include using room-temperature air instead of steam; no rotational effects; low inlet pressures; and venting to atmospheric pressure. The YFT code was then run with these modified case files to provide a comparison with the measured data to come.

Fifty pressure tap holes were EDM-drilled onto strategic locations in all 6 cavities and inlet and exit flowpaths of a second-stage bucket. Two bucket castings with half of the airfoil surface removed (one suction side, one pressure side) were used to check and adjust pressure tap locations to guarantee that no taps would hit turbulators. Tube fittings were fastened at each of the 50 locations, casting holes were plugged, and hardware was fitted to the inlet and exit of the bucket to match the YFT model and interface to the plenum. Total flowrates were measured for each of three inlet pressures and compared with the YFT solution. The YFT model overpredicts the amount of coolant flow. Tests are in progress to document the pressures at all 50 taps to identify areas of the YFT model that need to be modified to improve fidelity. These detailed tests will be continued in 1Q98.

Plans for Next Quarter

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

Technology Application

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

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

Objective

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

Progress for this Quarter

Stainless steel test plates were installed in a cold-flow wind tunnel and heated from the backside via imbedded cartridge heaters. Each plate was instrumented with several pairs of thermocouples arranged to form heat flux gauges. The test side of each plate was coated with TBC. One plate was left as an uncoated metal surface and served as the hydraulically smooth surface baseline.

Test conditions covered a representative range of flow Reynolds numbers, surface roughness, and step height-to-momentum boundary layer thickness ratios. Two TBC coated plates and one hydraulically smooth metal plate were tested. Plate average Reynolds numbers ranged from 400,000 to 3,600,000. TBC surface roughness levels ranged from 1 to 10 microns (40 to 400 microinches). Step-height-to-momentum boundary layer thickness ratios from 0 to 20 were tested for each roughness level. Repeatability was found to be very good for the metal plate results and satisfactory for the TBC-coated plate results.

The results of this task show that, for the majority of the airfoil and endwall surfaces, polishing to a roughness level on the order of 2.5 to 3.0 microns (100 to 120 microinches) provides a significant reduction in heat transfer coefficients, whereas further polishing results in only minor improvements, which were indistinguishable from the experimental uncertainty. The relative effects of flowpath steps were found to be essentially the same whether the surface is smooth or rough. Heat transfer enhancements of up to 2.5 may be expected at the leading edge of an endwall step. Roughness did tend to cause a more rapid decay of the heat transfer enhancement factor downstream of the steps.

Plans for Next Quarter

This task has been completed.

Technology Application

Application of the data obtained from this task takes on two forms within the design of the turbine airfoils. First, tests which measure the effect of TBC surface roughness on external heat transfer will be used to determine the extent of necessary polishing for new parts. Second, detailed quantification of the heat transfer magnitude associated with actual TBC roughness will allow for more accuracy in the initial design of airfoils. The data obtained on flowpath steps will be 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 is 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 is 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 is specifically designed to lower the heat load on the airfoil. Results from the previous cascade tests are being 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 has no experimental basis for airfoils that deal with complex flows, it is necessary to verify the new design. Results from the original series of tests will be used to reduce the present task efforts to a minimum. Most of the original apparatus hardware from the ATS Turbine Inlet Nozzle Cascade will be reused for this task.

Plans for the Next Quarter

This task has been completed.

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 is heavily dependent upon the nonlinear effects of surface roughness, especially as the nozzle design cannot rely upon film cooling. Given the current state of turbine cooling technology, the only viable method for determining the nozzle heat load with roughness effects is experimental validation of the heat transfer distribution under non-dimensional engine-representative conditions.

The ATS Turbine Inlet Nozzle Cascade has been used to provide data on external heat transfer coefficients on airfoils with surface roughness. The cascade incorporates instrumented airfoils with flow conditions representative of the ATS inlet nozzle geometry. The appropriate non-dimensional parameters for dynamic similarity are close to those of the engine inlet nozzle. External heat transfer coefficient distributions are 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 include various roughness levels, distributions, and types to allow the calibration of predictive methods. Characterization of surface roughness effects includes the interactive nature of roughness with fluid dynamic conditions such as acceleration. The cascade has also been used to assess the effects of transition piece wake shedding on airfoil heat transfer, the effect of extreme surface roughness representative of as-sprayed thermal barrier coatings, and the effect of modeled coating spallation on heat transfer enhancements.

Plans for Next Quarter

This task has been completed for the current cascade airfoil configuration.

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

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

Progress for this Quarter

A tophat specimen with a fillet geometry and a Pt/Al topcoat was thermally cycled for 200 cycles. The cracks in the topcoat became visible in a dye penetrant test. The pattern of the cracks is being interpreted as an indicator of the strain profile in the specimen.

A TBC-coated fillet specimen was run and accumulated 2500 cycles. The thermal profiles observed during the test were unexpected and indicated that the thermal resistance of the coating is greater than anticipated.

Plans for Next Quarter

The latest fillet tophat data will be analyzed. A specific objective of the analysis will be to determine whether the thermal properties of the coating are in fact different from those expected. A second fillet test is planned, but the experimental protocol will depend upon the analytical results from the first test.

Technology Application

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

Section 2.2.3.8 (GTETSP) Steam Particulate Deposition

Section 2.2.3.8.1 (GTETSP) Steam Particulate Deposition Rig Testing

Objective

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

Progress for this Quarter

The primary activity was continuing to transition to GEPS staff the knowledge gained from the previous studies. This included reviewing vendor proposals for the plant steam filter arrangement, and recommending best practices, based on the experimental experience. The

experimental results from the static specimen exposures (as reported earlier) continue to provide encouragement that the ATS plant with this filter will be able to reach the 24000-hour TBO target set for the plant. The filter design includes the ability to gain access to the filter vessel quickly during a short outage, should that be required. Procedures for instrumenting and operating the filter system have been agreed upon.

Plans for Next Quarter

The test portions of this steam purity task have been completed. One final vendor visit is planned and arrangements will be made for disposition of the experimental equipment.

Technology Application

The proper particulate filtering of steam used for bucket and nozzle cooling is critical to the reliable long-term operation of the ATS gas turbine. Data from tests under this steam particulate deposition task made it possible to establish the necessary steam filter specifications.

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 (LCF), and creep. Additional tests deemed necessary to meet design criteria will be performed. Comparisons will be made to data collected in air. Where necessary, the program will evaluate the roles of alternate heat treatments and/or surface treatments.

Progress for this Quarter

Fatigue crack propagation testing of IN718 material continued. Data were tabulated from additional heats and forgings to enhance the resultant mechanical property curves. Dynamic crack growth rate testing in steam continued on specimens from the first piece qualification (FPQ) IN718 forging. Creep testing in steam continued beyond the 6000-hour mark.

All tensile and creep tests were completed with parent metal and welded specimens of IN718. Fatigue testing with sheet specimens is still in progress. Examination of the mechanical properties of an alternative material for rotor steam delivery components continued. Tensile tests were completed and stress strain curves were issued to Design Engineering. Slow strain rate tests (SSRT) were completed on this alternative material.

Machining of mechanical test specimens for hot gas path materials destined for testing in steam continued. Additional test specimens were machined from cast slabs made of the first-stage nozzle material. Specimens machined included 15 low cycle fatigue (LCF) samples and 16 crack growth rate samples. Cast slabs of the third-stage nozzle material were received from the foundry, and machining of specimens was initiated to support creep, LCF, and crack growth rate testing.

Plans for Next Quarter

Additional samples of material from IN718 forgings that are the product of "Ingot 4" will be subjected to dynamic crack growth rate threshold testing in steam. The following tasks will continue: LCF testing of IN718; fabrication of high priority welded and brazed joints to permit characterization of mechanical properties of hot gas path material joints; slow strain rate tensile (SSRT) tests of these joints to identify areas of subsequent analysis and initiate LCF testing; crack growth, creep, and LCF testing of hot gas path material specimens in steam; machining of mechanical test specimens from the third-stage nozzle material; and LCF testing of rotor steam delivery material specimens.

Technology Application

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

Section 2.2.4.2 (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 for Next Quarter

This task has been completed.

Technology Application

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

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

Objective

The objective of this task 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.

Progress for this Quarter

Approximately 2000 more hours of exposure time were accumulated in the high-temperature oxidation burner rigs on several different coatings. Metallographic evaluations were performed on those few pins that were removed from test. Strain-to-crack tests continued, with the objective of permitting relative ranking of the oxidation results and subsequent comparison with field performance results to validate this testing approach to new coatings.

Plans for Next Quarter

Burner rig testing will continue. Strain-to-crack testing at various temperatures on all coating compositions of interest will continue. Test data will be analyzed and the results correlated with observations made on field-tested parts.

Technology Application

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

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

Objective

Although material selections have been completed, this task 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 (HCF) properties. For the 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 for Next Quarter

This task has been completed.

Technology Application

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

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

Objective

Information to support selection of materials for the variable guide vane (VGV) bushings and thrust washers 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 for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.4.6 (GTMTCS) Compressor Structural Materials and Processes

Objective

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

Progress for this Quarter

High cycle fatigue (HCF) testing of one of the compressor rotor wheel materials was completed and a final test report written. GE continued technical support of the diffuser supplier to address manufacturing issues that were discovered during the casting of the prototype diffuser. Tensile and low cycle fatigue (LCF) tests were performed on specimens taken from production castings to correlate part properties with previously collected handbook curves. The data from the parts exceed the handbook values. An alternative manufacturing process for the diffuser was proposed to move from a single, integral casting to a fabrication of investment cast pieces. The proposal continues to be reviewed for merit.

Plans for Next Quarter

Program staff will participate in additional supplier meetings as warranted. Evaluation of an alternative method of manufacture will continue.

Technology Application

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

Section 2.2.4.7 (GTMTRF) Turbine Rotor Forging Materials and Processes

Objective

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

Progress for this Quarter

The first set of IN718 forgings was received by GE during the first seven months of 1997. Ultrasonic inspection of these parts was completed using a newly developed automated test

system. Several forgings were found to have ultrasound indications that warranted additional evaluation that extended into this reporting period. The forgings were evaluated, and during this process several new software tools were developed and used to enhance the ability to image defects and material structure noise. Work continued to explore a correlation between the ultrasound results and specific features in the forgings. Smooth bar low cycle fatigue (LCF) with two different hold times and at two different temperatures continued in this reporting period. Twelve creep tests taken from "Ingot 3" and five creep tests taken from "Ingot 4" IN718 forgings were completed. A complete package of tensile test curves was added to the handbook. Crack growth rate, hold time testing, and static and dynamic crack growth rate testing of IN718 continue. Fracture toughness and high cycle fatigue tests were conducted on samples of the wheel material taken from various forgings.

Plans for Next Quarter

Exploration of the correlation of ultrasound results to features in the forgings will continue. Crack growth rate tests, creep rupture tests, LCF tests, and static and dynamic crack growth rate tests will continue. As appropriate, the handbook curves will be updated to reflect the results of these tests.

Technology Application

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

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

Objective

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

Progress for this Quarter

The primary focus of Materials Engineering activity was in the support of component suppliers as they work the production scale-up issues in the manufacture of these parts. Visits were made to the manifold suppliers to confirm the validity of process development work. Project plans with objectives and milestones were established for each of the key processes that still require fine tuning. An alternative E-beam welding service supplier was identified and visited to enhance our options in the manufacture of the manifolds. Additionally, a development program was launched to explore an alternative welding process with the Edison Welding Institute in Columbus that could be applied to the manifold. GE support of process development activity also occurred at the elbow supplier and the bore tube supplier.

Block-on-shoe fretting testing of four candidate coating systems was concluded. The fretting rig was assembled, and testing was completed at two temperatures in an air environment and at two temperatures in a steam environment. Work was initiated to qualify suppliers to apply the top-performing coatings on production parts.

Plans for Next Quarter

Welding procedure development will continue for the various processes at the locations noted under "Progress for this Quarter." Test results collected on first piece qualification (FPQ) samples will be evaluated to complete supplier qualifications. Revisions to the casting acceptance criteria specification will be made as needed, based upon the results of continuing mechanical property tests for these materials as a function of processing, with the goal of defining the optimum process that delivers the desired properties, and then documenting those conditions in the governing specification. Weld qualification will continue, as parts and test data become available. Additional block-and-shoe wear tests will be conducted on the top-performing coating. A comparison of the processing techniques will be investigated to optimize the coating process. Mechanical characterization of the coating and the composite of the substrate-coating system will be initiated. Support of Design Engineering reviews will continue as warranted.

Technology Application

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

Section 2.2.4.9 (GTMTSB) Structural Bolting

Objective

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

Progress for this Quarter

Stress relaxation tests continued on two different bolting materials. Data for one of the materials were gathered on two different heat lots.

Plans for Next Quarter

Collection of long-term relaxation data will continue, and the influence of pre-conditioning on stress relaxation response will be investigated further.

Technology Application

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

Section 2.2.4.10 (GTMTTA) Turbine Airfoils Materials and Processes

Objective

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

elevated temperatures. Metallic coating systems will be developed for internal and external oxidation protection of the airfoils. Samples will be coated using various techniques for optimization studies and process verification.

Progress for this Quarter

Tensile, creep, and low cycle fatigue (LCF) tests were conducted on hot isostatically pressed (HIPed) third- and fourth-stage bucket material at two different temperatures. The purpose of these tests was to determine the effects, if any, of HIPing on mechanical properties in this material. LCF testing at four selected temperatures was initiated on 23 aft-stage bucket material specimens that contained defects. The defect types being evaluated included shrinkage, porosity, and inclusions. In addition, high cycle fatigue (HCF) testing at five temperatures was initiated on nominally defect-free material. Additional third-stage nozzle material cast slabs were obtained from a foundry. These slabs will be machined into various test specimens. Additional design curves were issued for the aft-stage bucket material and the third-stage nozzle material. These included tensile stress-strain curves and HCF Goodman diagrams.

Consensus was achieved with Design Engineering and Life and Method Management regarding the types of testing to be performed for lifting the welded and brazed airfoil joints. Material was obtained for testing and test vendors were identified.

Testing to determine the effect of HIPing on the mechanical properties of the second-stage nozzle material continued. Creep testing and tensile testing were completed and a report was issued to Design Engineering. Curves for various tensile properties and creep were issued as revisions to the handbook.

Plans for Next Quarter

LCF tests on second-stage bucket material containing defects will be completed. HCF tests on nominally defect-free second-stage bucket material will be completed. Additional test specimens will be machined from the cast slabs of third-stage nozzle material. Standard specimens will be made for testing of airfoil joints. As many joint LCF tests as possible will be completed. LCF testing of the HIPed second-stage nozzle material will be completed. Handbook Curves will be issued following an analysis of these data. One additional heat of HIPed material will be obtained to determine the precision of the data.

Technology Application

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

Section 2.2.4.11 (GTMTCB) Combustion Materials and Processes

Objective

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

Progress for this Quarter

A test matrix for evaluation of sheet material with tensile, creep, and low cycle fatigue (LCF) of welded structures was agreed upon. Test material was machined for tensile property evaluation and LCF. Welded test specimens were made for LCF and tensile specimens were started.

Plans for Next Quarter

Base metal LCF and tensile testing will be completed. Machining of creep specimens will be initiated and testing started. Welded test specimens will be completed and testing started. All results will be reported to Design Engineering.

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.

Progress for this Quarter

Process refinements were evaluated and pursued with suppliers as need warranted. Iterative evaluation of supplier capabilities with Design Engineering was concluded.

Plans for Next Quarter

Support of the suppliers' metallurgical activities will continue, and first piece qualification (FPQ) results will be reviewed as they become available.

Technology Application

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

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.

Progress for this Quarter

Fabrication of the inner turbine shell was completed. The outer turbine shell is complete.

Plans for Next Quarter

Pertinent supplier qualification issues will be closed out.

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 using developmental hardware and samples.

Plans for Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.4.14.1 (GTFFTSESV) Hot Gas Path and Transition Piece Cloth Seals

Objective

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

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

Progress for this Quarter

Hot Gas Path Cloth Seals

The seal/slot thermal analysis was completed, and a detailed report on all 1997 seal testing and analysis was written.

Transition Piece Cloth Seals

Low cycle fatigue (LCF) tests were conducted on an outer cloth seal sample. The tests used the special high-temperature rig fabricated for the LCF test. The rig provides a controlled high-temperature environment and an oscillating mechanism to permit low cycle deformation of the seals being tested. The range of motion used in testing the cloth seal sample was representative of the relative movement between the ATS transition piece and the first-stage nozzle in going from fire-up to full speed, no load (FSNL) conditions.

The LCF tests were run for 1600 cycles. Leakage measurements were made before, during, and after the 1600 cycles. No appreciable deterioration in sealing occurred after 1600 cycles in the FSNL and steady-state conditions. A permanent set in the cloth seal was observed at fire-up conditions.

Plans for Next Quarter

Hot Gas Path Cloth Seals

The inner shroud, outer shroud, and nozzle junction cloth seal designs will be completed. The effect of curved continuous cloth seals (corner leakage) will be evaluated and compared with the effect of two-piece straight corner junctions. The high-temperature oxidation resistance of various cloth seal materials will be evaluated. Thermal analysis will be used to evaluate seal and slot temperatures and cooling requirements.

Transition Piece Cloth Seals

The following developmental tests are planned: leakage and LCF testing of the inner seal; leakage testing of the inner and outer seal at the segmented first-stage nozzle interface; natural frequency measurement of inner, outer, and side seals; leakage test of the seal system (i.e., full transition piece end frame, outer, inner, and side seals); revised outer seal shim analysis with latest growth/stack-up information; and outer seal leakage test of tolerance for gap with first-stage nozzle.

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

Progress for this Quarter

There are two seal locations to be considered: aft of the steam scroll is a leakage flow with a low-pressure drop; forward of the scroll is a leakage flow with a high-pressure drop. A single-stage brush seal design was developed for the first location and a two-stage brush seal for the second. Static leakage tests were used to determine the leakage performance under operating conditions. Computational fluid dynamics (CFD) modeling was used to design the geometry of the two-stage seal. Since most wear is assumed to occur during transients, the wear life is being determined by testing under conditions based on extreme transient conditions. The design will be validated by sub-scale rotary tests under operating conditions.

The objective of the dynamic leakage test is to measure seal leakage during rotation and to determine the durability of the two-stage seal design in a high-pressure steam environment. The steam deposition test rig was modified to accommodate 4 brush seals: one brush seal set consists of unsegmented seals, the other set is segmented with the segment end design similar to that of the H machine. Both sets of brush seals have 4 labyrinth teeth between the brush seal stages and a 44.5-mm (1.75-inch) spacing between the last labyrinth tooth and the second brush seal.

Leakage tests were completed. Seal durability was demonstrated and seal leakage was measured at pressures of up to 2.34 N/mm^2 (340 psi), the maximum pressure achievable with the test rig system, and at steam temperatures up to 371°C (700°F). Inspection of the brush seals showed no flow-related damage.

Seal leakage was measured with and without shaft rotation. The static leakage data agreed well with predicted flowrates. During the dynamic leakage test, contact occurred between the rotating shaft and the backing plate of the brush seal in the radial direction. The rub resulted in increased leakage past the brush seals. The rub occurred on an approximately 90° sector of all four brush seals. The cause of the rub is believed to be non-uniform thermal expansion of the seal holder housing which results in an eccentricity between the shaft and the seal holder housing. Away from the rubbed areas the brush seals showed minimal signs of wear. As a result of this test, the brush seal backing plate design will be modified to avoid rubbing and minimize the effect of a rub on the brush seal performance.

Plans For Next Quarter

This task has been completed.

Technology Application

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

Section 2.2.4.15 (GTMTAR) Airfoil Repair

Objective

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

Progress for this Quarter

Refinement of repair techniques for the first-stage bucket and nozzle material continued. Laboratory-produced brazes and welds were evaluated and screened based upon limited mechanical property tests. The first set of trials on production hardware was successfully completed. E-beam welding processes were continued for the repair of equiaxed casting materials. Radiographic examination inspection methods were verified for these joints.

Plans for Next Quarter

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

Technology Application

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

Section 2.2.5 (GTTT) Thermal Barrier Coating Technology

Section 2.2.5.1 (GTTTSD) Coating System Development

Objective

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

The TBC manufacturing technologies portion of the task will focus on integration and compatibility between TBC processing and other component manufacturing steps. Techniques to prepare components for spraying will be defined. Fixturing and masking will be developed. Surface finishing techniques will be developed.

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

The TBC nondestructive evaluation (NDE) portion of the task will develop NDE techniques to measure attributes and properties of TBCs on turbine hardware that are relevant to

manufacturing. The primary focus will be on development of methods to measure coating thickness. A secondary focus will be on development of methods to evaluate coating microstructure

Progress for this Quarter

Robotics Motion Control and Programming Methods for Airfoils

The three FANUC Robotics M710i/RJ2 systems (two development systems located in Schenectady, NY; one production system located in Greenville, SC) were configured to assure matched performance. A Visible Laser Measurement System was developed for use by the robot operator during motion verification.

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

Two off-line robotics motion simulation systems were developed and tested. The first is a Tecnomatix product called ROBCAD, which supports full 3D modeling of robotics motion with capabilities for detecting motion limits (position and velocity) and collisions. The ROBCAD/STP programming tools are in place, and motion development for ATS hardware is underway. Planned ROBCAD enhancements will further improve functionality and reduce the amount of time required to perform collision detection. The second simulation tool is a GE Corporate Research and Development (CRD) product called Coordination through Short Motion Programming (CSMP). CSMP takes into account the robotics system capabilities for motion position, velocity, and acceleration based on equipment characterization studies performed at CRD. Version 1.0 of the ROBCAD Advisor software program was provided to GE Power Systems (GEPS). This software will serve as a base platform upon which further CSMP functionality will be incorporated.

Initial motion programming approaches for nozzles and buckets were selected. Designed experiments are being used to optimize motion programming for various parts. ROBCAD software was installed at CRD and gun motions were successfully transferred between GEPS and CRD. This will enable the development of new motion programming strategies to occur simultaneously with production support.

Nozzle Coating Trials

Production ATS first- and second-stage nozzle castings were received for coating trials. A second-stage ATS turbine nozzle was coated and evaluations began.

Bucket Coating Trials

One ATS bucket replica was coated and evaluations began. Production ATS first- and second-stage bucket castings were received for coating trials.

TBC Process Development for Transition Pieces

Work resumed on developing a process for a thick TBC on ATS transition pieces. Critical plasma-spray process parameters were identified. Improvements in TBC properties to nearly 5X over baseline production coatings were achieved. A preliminary set of processing parameters was selected.

An ATS transition piece to be used for combustion testing was coated in the production spray cell using the preliminary process parameters. Metallography confirmed that the microstructural features of the TBC were significantly improved over conventionally processed transition piece coatings.

Bond Coat Process Development

Testing and evaluation of protective bond coats on substrate materials to be used for first- and second-stage airfoils, shrouds, and transition pieces continued with additional furnace cycling and oxidation rig hours accumulated. Based on the data received to-date, bond coats for the first ATS hardware were selected, and specifications were written for the materials and techniques chosen.

TBC Manufacturing Technologies

Evaluations and calibrations of non-robotic booth equipment were performed to assure equivalency among three GE sites. A survey of sites was conducted to identify the differences in the spray procedures being used to apply TBC. The survey covered 142 different spray parameter, equipment, or procedural choices. Common settings for all parameters were identified and included in the TBC process specification.

Controlled TBC surface finishing methods are being developed to ensure both acceptable surface finish and uniform material removal over all regions of the airfoils, fillets, sidewalls (nozzles), and platforms (buckets). Smooth TBC surface finish has two benefits: (1) it lowers TBC and metal temperatures by reducing hot side heat transfer, and (2) it enhances machine performance by reducing aerodynamic losses. Conventional finishing techniques, such as tumbling and grit blasting, were not acceptable because the differences in removal rates at different locations (e.g., fillets and leading edges of airfoils) make it impossible to maintain a uniform coating thickness. Continued development is focusing on CNC machining operations such as grinding, belting, or milling. A different technique, which utilizes part-specific soft tooling and conformable abrasive media, also showed good initial results and is being further evaluated.

Profilometer settings for the measurement of TBC surface finish were completed. The specification provides a means of comparing surface roughness readings from different sites through a calibration to a standard profilometer and reference coatings.

Several processes for applying bond coat and top coat to the welded joint of the second-stage nozzle doublets are being evaluated. These nozzles are cast as singlets and welded into doublets following application of TBC to the nozzle airfoil and sidewall surfaces.

Metallurgical evaluation showed that the weld process has minimal effect on the TBC structure. However, access to the weld joint is not adequate for the application of advanced TBC using the standard spray equipment. As a result, four approaches are being investigated: (1) use of an air plasma mini-gun for top coat and, possibly, bond coat deposition, (2) use of a braze alloy for the bond coat, (3) use of a slurry-applied ceramic for the top coat, and (4) use of an HVOF bond coat process.

An air plasma mini-gun that is capable of producing good TBC microstructures with acceptable deposition efficiency and reliability was identified. Slurry-applied ceramic top coats were abandoned because of the poor mechanical properties of the ceramic.

Variations of brazed bond coat—including alloy composition, surface roughness, and deposition method—were evaluated. One-inch diameter coupons were prepared and coated with TBC by air plasma spray (APS), except for a 6-mm (0.25-inch) stripe in the center of each coupon which was masked, simulating the weld-joint. The brazed bond coats were applied to the masked areas. TBC was then applied to the brazed bond coat by either APS or liquid slurry deposition technique. The test coupons were thermally aged using both furnace (furnace cycle test) and torch (jet engine thermal shock test) apparatus. Several variations of brazed bond coat significantly outperformed the baseline APS bond coat; however, development work will continue in order to optimize the brazed bond-coat/ceramic interface roughness.

An HVOF spray process is being evaluated for application of the bond coat to the weld joint. Although the HVOF gun will not fit in the area between the nozzle airfoils, that is not expected to be a significant limitation because the process employs a much longer standoff distance and is more tolerant of off-angle spray than the APS process. HVOF bond coat specimens from a previous design of experiments (DOE) are being evaluated for surface roughness and coating microstructure. Additional specimens are being fabricated that better simulate the geometry of the weld joint. These specimens will be used to address masking and gun motion issues.

Techniques for applying TBC over strain gauges were evaluated. Trial plates were fabricated by applying a standard TBC bond coat and top coat followed by a heat treatment. The TBC was then locally removed by the gauge vendor for installation of the strain gauge. A ceramic overcoat was applied by the vendor to restore thermal protection in the gauge region.

TBC Process and Diagnostics

Plasma guns that operate at longer standoff distances and higher powder injection rates are desired for manufacturing. Experiments were performed to evaluate coatings sprayed using four different guns. Preliminary analysis of the data suggests at least one gun has the capability to achieve TBC properties similar to those achieved by the present plasma gun at much longer standoff distances and up to 4X higher powder injection rates.

Parameters for measurement of TBC deposition temperature were specified. A radiative heat transfer model was used with reference specimens to determine the temperature error caused by the optical transmission through the TBC in a moderate temperature gradient. Software developed by CRD will be used for automated data collection.

Nondestructive TBC Thickness Measurement

An automated ceramic coating thickness measurement system using a flexible eddy current probe in combination with a multi-axis contact probe scanner was developed. Installed Coordinate Measuring Machines (CMMs) in Schenectady and Greenville will be used as the scanning devices. The other elements of the system include redesigned eddy current probes, a redesigned probe holder, a Nortec 24 eddy current instrument, a Pentium computer, motion control software, and a modified version of the eddy current software being used for manual eddy current measurements. Two flexible eddy current probes of different configurations will be used initially to fully inspect ATS nozzles and buckets. Further system development will focus on use of miniaturized rigid eddy current probes.

CMM motion programming and control is performed using a Tecnomatix software product called VALISYS. This software was installed and successfully tested with the automated inspection system. Part fixture specifications were developed for ATS nozzles and buckets. Tooling vendors were selected and the fixture designs are complete. Orders were placed for one set of development fixtures.

A test matrix for determining the effect of variations in the ceramic coating and bond coat thicknesses on the measured ceramic coating thickness was planned. Additional thickness calibration specimens will be constructed using the newly developed bond coats as well as the substrate alloys corresponding to the various ATS buckets and nozzles.

Nondestructive TBC Microstructure Evaluation

Laser ultrasound will be used for nondestructive evaluation of TBC microstructures. The laser ultrasonic approach uses a Nd:YAG laser to produce a shaped source beam onto the target coated substrate, generating an ultrasonic Lamb wave that propagates in the coating. A laser interferometer senses the propagating wave signal, which is stored on a computer and analyzed for frequency dispersion content, i.e., ultrasonic velocity as a function of frequency.

Young's modulus and tensile properties can be determined from the dispersion properties using an analytic model. The model indicates that dispersion properties are sensitive to coating mechanical properties and not to the bond line roughness. The coatings contain anisotropy (in-plane vs. through-thickness) and are not adequately described by a single number. Inversion tools for extracting all relevant moduli are under development.

Plans for Next Quarter

Robotics Motion Control and Part Programming Methods for Airfoils

Calibrations to establish robot equivalency will be completed. Motion trials and TBC coating trials using the ATS nozzle replica will be performed. Motion trials and TBC coating trials using the ATS bucket replica will be performed.

TBC Manufacturing Technologies

CNC grinding trials for finishing TBC on airfoils will be conducted at a vendor site. Process development for coating of the second-stage nozzle weld joint will continue. New brazed bond coat samples will be fabricated and tested. HVOF bond coats will be applied at various

process parameters and subsequently coated with TBC by mini-gun. Mechanical properties and thermal cycling tests will be conducted.

TBC Process and Diagnostics

One alternate plasma gun will be selected for focused development. Specifications will be established for automated IR data collection. Temperature error at high thermal gradients will be determined using IR temperature standards. Experiments to evaluate APS repair of an as-processed TBC will be completed.

Nondestructive TBC Thickness Measurement

The integration of the motion control computer and software with the scanning hardware for the Mark 1 automated eddy current thickness scanner will be completed. The system will be beta tested using an ATS nozzle. Metallographic measurements of bond coat thickness on specimens will be correlated with eddy current measurements using the flexible probe system. Compound curvature specimens will be built.

Nondestructive TBC Evaluation

A quality function deployment (QFD) will be held with GEPS to define the requirements for transitioning the laser ultrasound technology to production.

Technology Application

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

Section 2.2.5.2 (GTTTRR) TBC Risk Reduction

Objective

TBC durability will be evaluated under conditions very similar to the surface temperature, thermal gradient, and stress state of TBCs in ATS applications. An E-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 different microstructures and deposition techniques, the role of number of cycles and hold times at high temperature on TBC failure mode, and the role of bond coat composition and roughness on TBC life and failure mode. The effects of environmental contaminants on TBC performance in high thermal gradient conditions will be investigated. Numerical modeling will be used to determine the stress, strain, and thermal gradient conditions in the various TBCs during the tests.

Progress for this Quarter

Two TBC-coated tophats were furnace aged to 50% and 75% of expected ATS TBC life. These tophats were then tested under full ATS conditions for 100 hours and 2500 cycles. No spalls or hot spots were observed during testing and no TBC damage was observed by cross-

sectional metallographic evaluation. Test specimens for residual mechanical property measurements were machined from these two tophat samples. No systematic decrease in the residual mechanical properties was measured.

The third CMAS tophat was tested under conditions that produced partial CMAS infiltration into the TBC. No TBC spallation occurred after 87 two-minute cycles, at which point the testing was stopped because of equipment problems. Samples were fabricated for metallography and mechanical testing.

Testing of a fillet TBC endurance tophat began under full ATS conditions. The TBC was machined to produce a uniform thickness in the fillet region. No spalls or hot spots were observed during the first 1000 cycles of testing; however, the TBC top surface ran hotter and the metal ran colder than expected as a result of the increased thermal resistance of the coating in the fillet. The higher thermal resistance is caused by high porosity and poor splat-to-splat bonding, which result from geometric effects during the spray process.

Plans for Next Quarter

Fillet TBC endurance samples will be tested at full ATS conditions until 100 hours and 2500 cycles have accumulated or a TBC hot spot is observed. Samples furnace-aged to 0%, 50%, and 75% of expected ATS TBC life will be included. Metallography and mechanical testing of the third CMAS sample will be performed. The fourth CMAS sample will be tested until 250 cycles or a TBC hot spot is observed. The 13 μ m IR pyrometer for measurement of TBC surface temperature will be installed and tested.

Technology Application

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

Section 2.2.5.3 (GTTTDD) TBC Design Data and Life Analyses

Objective

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

The relative contribution of oxidation and cyclic damage to the failure of two TBC systems will be evaluated in order to estimate the TBC life under the ATS gas turbine conditions. This will be accomplished by furnace cycle testing TBC systems using a series of dwell times per cycle (0.1 to 20 hours/cycle) and dwell temperatures (1037°C-1148°C, 1900°F -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 thermomechanical fatigue test that superimposes cyclic mechanical strain upon the cyclic thermal strain. In

support of the modeling approach, microstructural features of the bond coat and ceramic top coat will be examined.

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

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

Progress for this Quarter

Furnace Cycle Test

Porous and dense vertically cracked (DVC) TBC specimens were furnace cycled at 1148°C (2100°F) and 1093°C (2000°F) using dwell times of 0.1, 0.75, and 10 hours per cycle. Preliminary evaluations of the test data and failed specimens showed that approximately equal contributions of bond coat oxidation and ceramic fatigue control TBC system life at temperatures of 1093°C (2000°F) and above.

Thermal Conductivity

(A) Planar samples

The primary objective was to produce refined design data for TBC thermal conductivity as functions of temperature and aging time. Samples were aged in air for 1000 hours at 1038°C, 1204°C, and 1316°C (1900°F, 2200°F, and 2400°F). These samples were compared with corresponding samples aged for short times (<100 hours). There was no measurable change in TBC density as a result of aging.

(B) Curved TBC samples from parts

Sections from production first-stage buckets were evaluated. There was higher scatter in the thermal conductivity compared to planar samples, which is consistent with a larger error in thickness and density compared to planar samples. Within the measurement uncertainty, there was no trend in thermal conductivity corresponding to subclassification (e.g., run-to-run, convex vs. concave, large vs. small radius of curvature). However, the absolute value of thermal conductivity was slightly lower than the values measured previously on corresponding planar samples.

A correction factor for the systematic error in sample thickness measured on unpolished TBC was developed.

Plans for Next Quarter

Furnace Cycle Test

Exposures at 1038°C (1900°F) will begin. This task will interact with the NDE task by providing a matrix of samples on which laser ultrasound measurements can be made prior to tensile testing.

Thermomechanical Fatigue Testing

Samples will be prepared for thermomechanical fatigue (TMF) testing to provide data needed to predict TBC life at temperatures below 1038°C (1900°F).

Thermal Conductivity

Long-term sample aging will continue. Other priorities will be decided by consultation with the thermal conductivity working group. Improvement of the thermal diffusivity measurement is a continuing task. The major areas for further improvement are: (1) improvement of integrity of IR opaque coatings at high temperature, (2) reduction of IR detector non-linearity, (3) software analysis improvements.

Technology Application

A database will be established that 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 that result in improved properties and durability.

Section 2.2.5.3.1 (GTFFTB) Bucket TBC Roughness and Spall Characterization

Objective

This task will quantify the external airfoil heat transfer coefficients associated with the roughness characteristic of TBCs. This task places specific attention on 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 will use CRD's Transient Heat Transfer Cascade to test an airfoil coated with TBC that has been polished to various levels, and assess the effect of TBC-type roughness.

Plans for Next Quarter

This task has been completed.

Technology Application

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

Section 2.3 (CC) Combined Cycle Integration

Section 2.3.1 (CCUA) Unit Accessories

Objective

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

Designs of remaining accessory systems will be conventional.

Progress for this Quarter

Cooling-Air Cooling System

The functional specification and process and interface drawing (P&ID) were completed in 3Q97, and the selection process for a supplier of the cooling-air cooling skid was begun in 4Q97. A supplier was selected to develop the first skid and the skid's major components. Preliminary design reviews held between GE Engineering and the supplier resulted in the revision of the cooling-air cooling functional specification and P&ID.

Steam Cooling System

A design review resulted in the preliminary selection of a steam measurement system configuration. Based on this decision, the steam cooling system P&ID was updated. Work began with suppliers as to the type and size of flow meters that would be required for the system. Outline drawings for the steam valves and filter were marked up for size based on the increased steam cooling flow requirement, but were not released pending a final decision on the actual steam flow number.

Clearance Control System

Final design reviews were held prior to supplier selection. A supplier was chosen for the clearance control skid that will be responsible for the detail design, fabrication, and testing of the skid. In addition, GE engineers selected suppliers for the major components of the skid.

This was necessary in order to expedite the skid fabrication to meet shipping requirements in 1Q98. The skid ordering sheet and electrical diagram were completed.

Exhaust Diffuser

Results of the exhaust diffuser model testing completed at the end of 3Q97 showed that the aerodynamic design of the diffuser was satisfactory. In addition, the layout of the piping that will penetrate the exhaust diffuser was continued. Once the final configuration for the piping is established, a final model test may be required to ensure that no adverse aerodynamic effects are caused either by the piping or the changes in the flowpath due to the physical location of the piping.

Plans for Next Quarter

Cooling-Air Cooling System

An advance purchase order will be issued to release the skid supplier to begin the detail design and engineering work on the cooling-air cooling skid. This will involve several design reviews and design iterations throughout 1Q98 as the detail design is developed.

Steam Cooling System

Once the steam cooling flow is established, the outline drawings for the steam valves and steam filter will be revised accordingly. Upon final agreement on the configuration of the steam measurement system, the design of the system components will begin by completing the P&ID and development of the component outline drawings.

Clearance Control System

Several design reviews will be held between GE Engineering, the skid supplier, and/or the component suppliers as the clearance control skid is designed, built, and tested. Since it is a new system, the clearance control skid will be subjected to GE's first piece qualification (FPQ) process. By the end of 1Q98, the first clearance control skid will be built and shipped for use at the GE gas turbine test facility. The skid will be operated with the gas turbine and tested during 2Q98.

Exhaust System

A determination will be made as to whether the acoustic resonance discovered in the model test is severe enough to warrant its elimination, and if so, what testing will be necessary to learn how elimination will be possible. Development of the piping layout into the diffuser will continue. Once complete it will be possible to establish the flowpath of the diffuser. A final model test may be required to confirm the aerodynamics of the final flowpath configuration. Concurrent with this, the detail design will begin with the diffuser supplier which will be paced with the piping layout and CRD model testing being done.

Technology Application

Development of the cooling-air cooling system, the steam cooling system, the clearance control system, and the exhaust diffuser system are all critical to successful operation of the ATS gas turbine. Each system is also critical to the high efficiency rating that the ATS gas

turbine will achieve. Therefore development of these systems will continue in order that the ATS gas turbine meet these design goals.

Section 2.3.2 (CCCL) Controls

Objective

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

Progress for this Quarter

Control algorithms are being coded into control system programs and control loop dynamic studies are being performed, including: gas turbine clearance control, variable guide vane control, fuel control, and startup and shutdown sequences. Development of algorithms for the protection of the ATS gas turbine continues, focusing particularly on the protection of hot gas path components. Design and manufacturing processes for the prototype control panels of the integrated control system are nearing completion. Prototype field testing of the control components is on-going.

Plans for Next Quarter

Study of control loop dynamics will continue. Software algorithms and sequence logic for the gas turbine will be coded into control programs in preparation for running tests. Verification of the control programs will continue, using equipment models and actual control panels. Manufacture of the prototype panel for gas turbine control will be completed.

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

Technology Application

The integrated plant control system conceptual design for the STAG 107H configuration will be very similar to that of the STAG 109H 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 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 and effects analysis (FMEA) will be included.

Progress for this Quarter

Activity during this period was restricted to FMEAs.

Gas Turbine Flange-to-Flange - Turbine and Compressor

FMEA development continued on all conventional aspects of the turbine and compressor. Sixty-one FMEAs were identified to-date in Gas Turbine Flange-to-Flange. Thirteen FMEAs were completed. Sixty-one FMEAs were identified as of 4Q97 in Gas Turbine Flange-to-Flange, with 23 being completed, 16 in progress, and 22 yet to be started.

Plans for Next Quarter

FMEA development will continue on the following: stator system, combustion, stator structures, steam delivery system, rotor, and assembly FMEAs involving interface of Turbine Design Engineering and Compressor and Structures Design Engineering.

Technology Application

The FMEA results will be applied to the design of the 9H and 7H hardware, with special emphasis on the components involved with the steam-cooling aspects of the design.

Section 2.3.4 (CCSD) Combined Cycle Systems Design

Objective

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

Progress for this Quarter

The heat recovery steam generator (HRSG) configuration was modified to include a reheater in series with the gas turbine cooling circuit. This means that steam flow exiting the gas turbine is sent into the reheater before being admitted into the IP steam turbine. The series reheater configuration allows greater flexibility to eliminate steam temperature mismatch at the HP and IP steam turbine admission. The steady state performance model (SSPM) was updated for improved computational convergence at various combined cycle loads and ambient conditions. Updates were also made to reflect revised gas turbine design parameters. The SSPM was documented and forwarded to Applications Engineering for use in proposal support of H Technology power projects.

The thermal dynamic model (TDM) was updated with faster steam property subroutines to improve computational speed. Verification of valve sizing and gas turbine steam cooling control strategy was performed using the TDM with revised gas turbine design parameters. This verification was performed by running a hot startup, normal shutdown, unit trip, and flying restart. Work to verify a second computer platform for the TDM is 50% complete.

Plans for Next Quarter

The startup procedure will be revised to include protection of the steam turbine from overheating during opening operations of steam admission control valves. Extension of the performance model to include automation of design point calculations will continue. Work will continue on system operating limits and control strategy definition for use in the 9H gas turbine prototype. Work will also continue on improving speed and convergence of the SSPM. The SSPM for STAG 107H will be updated in accordance with commercialization needs. Creation of Design Standards and Guidelines Documentation for use by Combined Cycle Applications Engineering will continue.

The dynamic model will be updated for the series reheater configuration. Verification of a second computer platform for the dynamic model will be completed.

Technology Application

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

Section 2.4 (MF) Manufacturing Equipment and Tooling

Objective

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

Progress for this Quarter

The 9H IN718 turbine rotor forgings completed machining operations at a supplier and were shipped to GE's Greenville, SC, site, where dovetail broaching and finishing operations were completed. Some steam system components for the rotor cooling system completed manufacturing operations and were delivered to Greenville. Construction of a test stand for full speed, no load (FSNL) testing of H design gas turbines progressed to a point where the foundation work was completed and the building erected. All accessory and support components are on order to support completion by April 1998.

Plans for Next Quarter

The IN718 turbine rotor with steam system components will complete manufacturing and assembly for the first 9H machine. Construction of the FSNL test stand will continue toward the April 1 completion date.

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 assure fit-up of all components in very

restrictive areas of the turbine. An electronic simulation of these areas is being done in parallel to develop simulation technology for future applications. The TBC robot controllers will provide the thickness control for the TBC coating that is required for proper heat transfer properties in the steam-cooled turbine airfoil components.

Section 2.5 (IG) Integrated Gasification and Biomass Fuel

Objective

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

Progress for this Quarter

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

Plans for Next Quarter

There is no activity planned for this period.

Section 2.6 (DE) Pre-Commercial Demonstration

Objective

A commercial proposal will be prepared and submitted to the host utility.

Progress for this Quarter

Commercial activity remains high. Excess generating capacity in the domestic market continues to delay project approvals; however, commercial discussions (equity, price, shipment requirements, insurance premiums, performance levels, construction financing, and service agreements) with potential host utilities and power marketers continue to intensify.

Plans for Next Quarter

The next Utility Advisory Board (UAB) meeting is planned for 1Q98 to coincide with the 9H gas turbine assembly preparation for full speed, no load (FSNL) testing in 2Q98.

Section 2.7 (PM) Program Management

Objective

Within GEPG Engineering, an ATS Program Office will be established and a Program Manager and a Contract Administrator will be assigned. The Program Manager will direct the

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

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

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

Progress for this Quarter

In order to reflect the most current costs and an acceleration of the scope of work, GE Power Systems submitted an updated proposal to the Federal Energy Technology Center (FETC) to restructure the current ATS Phase 3 program. The updated proposal supersedes the proposal delivered in 3Q97 but retains the same Work Breakdown Structure.

As in the previous Phase 3 restructuring proposal, the work scope required to meet the 7H full speed, no load (FSNL) test was reviewed, and manpower and purchased services for each task were updated. Input from GE Power Systems Engineering and Manufacturing, GE Aircraft Engines, and GE Corporate Research and Development was included in the proposal, which was delivered in 4Q97.

GE Power Systems participated in the DOE-sponsored Advanced Turbine Systems Program Review held on October 28 and 29, 1997, in Morgantown, WV. The GE presentation reviewed the status of GE's ATS program and provided a comprehensive overview of the component design, rig test, and hardware production activities leading to the first ATS technology FSNL test.

Plans for Next Quarter

The proposal submitted in 4Q97 will be negotiated.