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Utility Advanced Turbine Systems (ATS) Technology Readiness Testing and Pre-Commercial Demonstration

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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 will be sited and operated in Phase 4. 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 2Q97. The most significant accomplishments are listed below:

9H/7H-common technology

- Implemented a field test program for bucket temperature monitoring
- Initiated 9H compressor rig testing at GE Aircraft Engine facility in Lynn, MA
- Completed final axial and radial clearance analysis for production 9H compressor and began detail drawings
- Compressor discharge casing casting completed first piece engineering and quality inspection and manufacturability process plan review
- Issued variable guide vane assembly, inlet, and compressor case instrumentation drawings
- Completed design of an exhaust diffuser with improved pressure recovery
- Shipped initial hardware to support full-scale combustor test
- Began production input for 9H fourth-stage bucket casting
- Completed first development trial on 9H second-stage bucket casting
- Shipped first set of 9H first-stage bucket to post-cast vendor
- Demonstrated ultrasonic contour-following and defect detection capability on first-stage bucket sample
- TBC robot-turntable programming produced a 3D-compatible TBC deposition system
- Initiated transition piece cloth seal life cycle fatigue (LCF) tests

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

In accordance with GE's ongoing Cooperative Agreement with DOE, a draft topical report covering Safety and Health, Permits and Licenses, and Environmental Protection was prepared by International Technologies Corporation for the 7H-related activities at the GE Power Systems manufacturing facility in Greenville, SC. DOE will use this information to prepare the NEPA documentation required for 7H manufacturing and testing activities.

Plans for Next Quarter

The draft report will be amended, if necessary, to reflect the DOE review results.

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 turbines (50 Hz) have similar flow paths 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 heavy-duty use design practices. The designs will be based on the GEAE CF6-80C2 compressor. Transient and steady-state thermomechanical stress analysis will be run to ensure compliance with GEPG life standards. Drawings will be prepared for forgings, castings, machining, and instrumentation for full speed, no load tests of the first unit.

Progress for this Quarter

The design of the 9H compressor is complete and all components were released for manufacture. The 9H compressor is on schedule to support the 9H program test requirements. During 2Q97, instrumentation and assembly drawing tasks were transitioned from the GE Aircraft Engine design team to GE Power Generation Compressor Design. They were initiated and will be completed during the next few months. Machining drawings for rotor instrumentation modification and some blade instrumentation drawings were completed.

A final assessment of the clearances prior to machine assembly and test is being performed to achieve good performance and operability of the compressor. This work includes a complete dimensional tolerance stack-up, a transient hot to cold deflection study, and an evaluation of off-design conditions such as stall. Final axial and radial clearances were specified on individual final blade and stator machining drawings and are now being worked on the blade and wheel assembly drawings, where appropriate.

The 9H sub-scale compressor test rig is now on test in the Lynn, MA, compressor test facility. Initial checkout and test runs to 80% corrected speed were completed. Final testing is planned for 3Q97.

The 7H compressor airfoil blade design and drawings for stages 3 through 14 and all stator stages are complete for the sub-scale rig. Stages 0 through 2 are still working. Rotor configurations and trade studies are being completed. Of particular importance is the selection of rotor and bolting material in the aft end.

Plans for Next Quarter

The 9H sub-scale rig test in the Lynn, MA. facility will be completed. Full validation of the 9H product aerodynamic and aeromechanical characteristics will be obtained.

9H product instrumentation and assembly drawings will be completed. Support for component manufacture will be provided as needed.

7H product and sub-scale rig definitions will be continued. The design will be completed and drawings released for sub-scale test of the remaining rotor airfoils (stages 0 through 3). The flowpath definition for the 7H compressor will be completed.

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

All test stand and combustor hardware was procured including the transition piece and seals, and the test stand was brought to a state of advanced build. Two more fuel nozzles were designed and their critical sub-components were cast. Preparations were made for test stand commissioning.

Plans for Next Quarter

The test stand will be commissioned and development testing will begin. A modification cycle for combustion components will begin. A fourth and final fuel nozzle design will be completed and sent to suppliers for casting and fabrication. Casting development for the production transition piece will continue.

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

Component modifications to the preliminary turbine rotor structural system model (transient thermal/mechanical) were completed. Further secondary flow iterations were made to improve flange closure. Rabbet interferences were adjusted and spacer bore diameters were modified to improve rabbet loads.

A spacer risk release review was completed allowing risk release of the spacers for machining. The review included system model flange and rabbet status as well as a preliminary life assessment of the spacers.

The third-stage 3D mechanical analysis was completed.

The second-stage turbine wheel 3D steady-state thermal mechanical analysis with and without the steam bushing was completed and shows minimal impact of the steam bushing on bolt hole, cooling hole, and dovetail slot bottom stresses.

The 3D mechanical analysis with 2D thermal sweeps for the 1-2 spacer was completed.

The first-stage turbine wheel final machining drawing was issued. The second-stage turbine wheel and 3-4 spacer final machining drawings are in final review.

Plans for Next Quarter

Further system model secondary flow studies will continue to completely close all flanges under all conditions. A 3D thermal mechanical analysis will be started for both the 1-2 spacer and the 2-3 spacer. The turbine wheel and spacer final machining drawings will be released.

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 (Task Force)

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

The transition disk was modified to include dowel pins located circumferentially along the centerline thru-bolt hole. Mechanical plane stress analyses were performed on pie slice cuts through the cross section containing the dowel pin. Initial stress results indicated extremely large hoop stress values along the inner radial location of the dowel hole. This large stress level was a result of locating the dowel hole too close to the thru-bolt hole. A large stress concentration effect coupled with a thin ligament produced stress levels greater than the acceptable value. Additional finite element analyses were performed to optimize the radial location of the dowel pin hole between the thru-bolt hole and outer rim of the transition disk. Hoop stress levels were reduced to acceptable levels.

Finite element analyses of the spoolies for the first- and second-stage bucket steam delivery system as well as the wear test specimen were performed. The analyses included contact elements with friction at all interfaces, elastic plastic material behavior, centrifugal loading, and angulation due to thermal expansion differences in the rotor. Acceptable assembly interferences to obtain required sealing and fatigue life were computed.

Finite element analyses of conceptual designs for the steam delivery system axial tube end retention method were performed. Because the original concept was found to be unacceptable, four more concepts were modeled and analyzed. The results are guiding changes in the design.

The 9H third-stage dovetails were analyzed and results are being reviewed. The dovetail is skewed 15.5° , which is at the limit of current product experience. The 3D model includes the

wheel and bucket with airfoil and was loaded with 3000 rpm rotation. Contact was modeled between the wheel and bucket.

A thermal system model of the rotor is being created to perform an LFE analysis. Two-dimensional meshes were created and the thermal and fluid boundary conditions are being prepared. The system model will include the aft shaft, bore tube end cap, bearing and housing, exhaust frame, and steam box. The work is concentrated on assembling all the turbine components into a single file and running this assembly under thermal loading.

Plans for Next Quarter

Mechanical design and analysis support for rotor components will be provided as needed.

Technology Application

The analyses performed and resulting design changes will be used in the final design. Analyses of the spoolies of the first- and second-stage bucket steam delivery systems resulted in assembly details that will be incorporated into the steam delivery design.

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 rabbit deflections is particularly important since this may affect rabbit opening/closure as well as rabbit 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

The thermal stress analysis of the aging process of the 7F first-stage wheel was completed without taking creep effects into account. Stress and strain data as a function of time have been obtained to determine appropriate test conditions for performing creep and stress relaxation tests. Creep and relaxation tests began for the IN706 material. When these tests are completed, the thermal stress analysis of the aging process will be redone using a creep model to determine residual stress levels after aging.

A heat transfer analysis simulating the quenching and aging process of the ATS gas turbine second-stage wheel was completed. Tensile tests were performed on specimens undergoing the same thermal history that was seen in the quenching and aging process. Stress-strain curves were generated as a function of temperature for specimens that underwent just the quenching thermal cycle and for specimens that underwent both the quenching and aging thermal cycles. These stress-strain data will be used to perform thermal stress analyses simulating the quenching and aging process of the ATS gas turbine second-stage wheel.

Plans for Next Quarter

Thermal stress analyses simulating the quenching and aging process of the ATS gas turbine second-stage wheel will be performed. Stress and strain levels will be obtained to provide test conditions for performing creep and stress relaxation tests on the IN718 material.

Technology Application

These residual stresses will influence the deformations of the wheel during overspeed. If they are found to be significant, they will have to be included in the design calculations for the ATS turbine wheels.

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 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. In addition to these effects, the performance prediction of the rotor steam circuit is based on the assumption that all parallel branches of the circuit behave identically. Non-ideal design and operational features will result in deviations from this ideal performance, but the extent of these deviations and their ultimate impact on bucket cooling is not presently quantified.

The rotational and 3D effects will be assessed using computational fluid dynamics (NOVAK3D), and the results of the analyses will provide the basis for design modifications as necessary. The impact of branch-to-branch variations will be evaluated using an expanded version of the rotor steam circuit network model (solved by YFT).

Progress for this Quarter

Computational fluid dynamics (CFD) analyses of the original bore inlet and supply end cap designs were completed. Results of these analyses confirmed flow swirl patterns previously predicted and pressure losses in the range predicted by the YFT analyses. A redesign of the end caps, driven by manufacturing and inspectability issues, was initiated and preliminary assessment of pressure drop penalties was performed using 1D analyses. CFD analyses of the alternate bore tube inlet section were performed. In addition to the baseline inlet design, a larger opening was also considered. The larger opening did not exhibit any undesirable back-flows through the inlet area and did improve the hydraulic performance of the bore inlet section (lower pressure drop, improved cross-sectional velocity distribution in the annulus, and slightly lower swirl angle). The results were transmitted and designers will incorporate the new design as the baseline.

A risk release review of the manifold design in which CFD results were presented was successful. Many CFD models of the supply and return manifolds were created as the manifold design evolved. The primary objective of the CFD simulations is to determine the magnitude of the flow maldistribution introduced by the manifolds in each bucket. The secondary objective is to verify the 1D pressure drop relations used in the overall steam

delivery circuit YFT model. Preliminary pressure drop analyses indicate that an adequate safety margin is available in the YFT steam circuit model.

A potential design improvement on the diffuser element of the bore tube discharge section was assessed and recommended.

Plans for Next Quarter

The CFD analyses of the steam distribution manifolds will be completed. As the end caps reach final definition, CFD analyses will be performed.

Technology Application

The results of this task define the hydraulic performance of the overall steam distribution circuit and of the individual components it comprises. Performance predictions of various designs were used in trade-off studies to select the baseline concept of the overall steam distribution strategy and the specific design of the scroll and the supply and return manifolds. Sensitivity studies will help anticipate the system response to perturbations.

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 this Quarter

This task has been completed.

Technology Application

All the design options evaluated in this study are being 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

A test pyrometer system was installed at the test site. The gas turbine is now running under normal operating conditions, and the pyrometer is generating data indicative of bucket surface temperature. The data will be used to help design the control and monitoring systems of the ATS gas turbine.

Plans for Next Quarter

Pyrometer data will continue to be monitored and analyzed at the test site.

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.

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

Design of the 7H turbine buckets continued. Detailed 2D and 3D analyses continued on the first- and second-stage dovetails as well as the third- and fourth-stage shanks. Additional casting trials were devised to better assess the castability and mechanical properties of candidate materials. Robust design activities continued with the development of response surfaces of LCF life as a function of various casting features for the 9H first-stage bucket. This model will be useful in fine tuning the 7H bucket designs as well.

Detailed design continued on all four stages of buckets for the 9H turbine. Instrumentation definition for the first ATS turbine has been completed and instrumentation drawings were issued. Casting trials were completed on all four stages. Production of the first set of castings is in process on the first and fourth stages, and nearly complete on the second and third stages. Robust design response surface models were generated for the first-stage bucket and used to estimate casting life on a piece by piece basis. Post-cast process qualification trials are in process at the various post-cast vendors.

Plans for Next Quarter

The first set of castings will continue for the second and fourth stages. First and third stages will ship to post-cast vendors. The second-stage bucket robust design response surface will be

completed and used in the disposition of castings. Instrumentation of the first set of hardware will begin. Post-cast processing trials and transient analyses will continue.

Analysis and optimization of the 7H bucket designs will continue with a view to electronic data release in 4Q97 for the various stages of buckets.

Technology Application

The design and development of turbine buckets are required for the ATS turbine to ensure that the buckets deliver power to the turbine shaft and the buckets 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.

Progress for this Quarter

The 9H second-stage turbine wheel/bucket dovetail 3D steady-state thermal and thermomechanical analyses were completed.

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 9H fourth-stage bucket shroud. A detailed 3D creep analysis is needed to ensure that the stresses are within the required limits for creep life.

Progress for this Quarter

The scope of this task was expanded to include the 9H third-stage bucket and analysis of a field-tested bucket for experimental confirmation. Work has begun on generating the fourth-stage bucket model.

Plans for Next Quarter

Elastic analyses of all three buckets will be performed.

Technology Application

The redesigned shroud will be used in the 9H fourth-stage bucket design. This analysis methodology will be repeated for the 7H fourth-stage bucket.

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) S1B Robust Design and Life Assessment**Objective**

The objective of this task is to develop design methods for buckets to minimize the influence of design and manufacturing variables. Statistical design methodology will be used to relax presently used worst case conditions (worst material, worst temperature, etc.) and develop capabilities to quickly assess bucket life.

Progress for this Quarter

The Design of Experiment (DOE) analyses for the first-stage bucket robust design and life assessment are complete. The factors included in the DOE are metal wall thickness, airfoil TBC thickness, TBC thickness in the leading edge, secondary orientation angle, primary orientation angle about the axial axis of the machine, and primary orientation angle about the tangential axis of the machine. This DOE yields prediction equations for alternating pseudo-stress and temperature. The prediction equations were transitioned to GE Power Systems in a spreadsheet-based life assessment tool that is currently being used to assess the life of production buckets. Robust design and probabilistic analyses were performed using these equations to determine optimum wall thickness and reliability curves for LCF life in critical bucket locations given current production parameters.

The first set of modifications and the addition of the platform to the second-stage bucket airfoil finite element model are complete. Baseline analyses were conducted and the critical life locations were identified.

Plans for Next Quarter

Work will continue on the robust design/life assessment of the second-stage 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 critical-to-quality criteria (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

The final report for the work being performed at Texas A&M University was completed. This report contains the minimum work scope requested by CRD to close out GE's contract with them. This effort was concluded with the attainment of repeatable test results for tip heat transfer coefficients. Texas A&M has provided two sets of tip heat transfer results for two geometries at two freestream turbulence intensity levels.

During 2Q97, a rebuilding of the Texas A&M cascade within CRD's test facilities was begun. It is approximately 90% complete and includes features added for increased flexibility in testing. Pressure-instrumented airfoils are being completed; the surface heaters are to be delivered. To avoid problems encountered in the past, this blade tip cascade will use a steady-state heat flux method with surface heaters to establish the heat transfer conditions rather than the transient blowdown method used by Texas A & M.

Plans for Next Quarter

CRD's new blade tip cascade will be completed. A safety check of the test section will be made before operation. Testing will be performed on tip geometries for comparison to the Texas A&M results. Further tests will establish the effects of rub-strip material loss and/or alternate positioning.

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 9H 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.

Progress for this Quarter

The ANSYS/LFE models of the first- and second-stage buckets were finished. Air-to-steam analyses were performed.

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. If the LCF life is too short with the present control plan, the air-to-steam transition rate will have to be changed to put the LCF life at an acceptable level.

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 over-utilization 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

Machining began on the required cascade slave airfoils for NASA's facility. The aluminum airfoil mold to be used by NASA in fabricating the heat transfer test airfoil was completed. The stainless steel ingot, which furnishes the slave airfoils, was heat treated and machined to parallel surfaces prior to wire-EDM of the airfoil. All drawings for instrumentation placement and dimensioning were completed.

Operating conditions within the NASA facility were reviewed with NASA test engineers. The proper blade Reynolds number requires an inlet cascade pressure of 25 psia. The NASA cascade is currently operated to a maximum of approximately 20 psia. NASA will explore the possibility of using higher pressure in their facility. If that option is not viable, the test Reynolds number for the first-stage bucket hardware will be reduced to approximately 80% of the desired value. That reduction is considered minor, as the results may be reliably scaled up to the desired conditions.

Plans for Next Quarter

All GE-supplied hardware will be completed. The airfoil mold will be shipped to NASA first to allow them lead time in fabricating the heat transfer airfoil. All other hardware will be shipped to NASA towards the end of 3Q97. Test initiation will depend on NASA's schedule.

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

Detailed heat transfer and stress analysis of the turbine nozzles and shrouds is being performed. Detailed flow analysis was performed to allow final definition of the cooling flow circuits. Nozzle covers and impingement inserts were defined and their fit-up was verified through 3D modeling. An overall detailed leakage/flow model was used to optimize component sealing. Component interfaces were completed.

Plans for Next Quarter

Further detailed design work will be performed so that the cooling and mechanical arrangement of the components can be completed. Parametric design studies will be carried out to optimize the design configuration. Detailed off-design flow calculations will be performed. Detailed 3D sub-modeling of critical areas will be performed.

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

Almost 100 ANSYS runs were made for the ATS Phase 3 design of experiments (DOE); the data thus obtained were analyzed, and response surfaces for stress, temperature, and life at each node were developed and verified. Using these response surfaces, Monte Carlo analysis was performed to calculate the probability of attaining a given LCF life value in the presence of different types of variabilities. Robust design studies were performed to maximize mean low cycle fatigue (LCF) life at each finite element (FE) node and to minimize life sensitivity with respect to variations, including manufacturing tolerances. The finite element model was further updated to incorporate design changes and to refine the mesh in critical areas of interest. DOE runs for lifing the castings received from the vendor were started. LCF life for a number of cast parts was assessed using ANSYS, and optimal TBC thicknesses for meeting the life requirements were determined.

Second-Stage Nozzle

The DOE study for improving LCF life on the basis of ANSYS analysis was completed. The results thus obtained for stress, temperature, and life are currently being analyzed.

Rotor Components

Spoolie Design: Further DOE studies were performed. Life values corresponding to the current design are improved relative to preliminary designs.

Steam Tube Bushings: A number of DOE runs were made and the numerical data were analyzed in detail. The present design meets the life and producibility requirements.

Manifold: Several DOE analyses were performed. As a result of these studies, a design was developed that meets producibility requirements.

Flanges: Analysis of the DOE data was completed. Design requirements were satisfied to an acceptable level, and drawings were released for the next step in the product development cycle.

Turbine Inner Shell

DOEs for both mechanical and thermal analysis were completed. Data were analyzed to identify parameters that have a significant influence on performance variables. 2D thermal results were substantiated against 3D analysis.

Plans for Next Quarter

First-Stage Nozzle

Updating of the FE model will be completed. Further studies on Monte Carlo analysis and robust design will be performed to improve the part producibility and the probability of meeting LCF life requirements. Execution and analysis of ongoing DOEs for lifing the cast parts will be completed. Response surfaces will be developed and validated. The LCF life of cast parts to be received from the vendor will be assessed, and optimal TBC thicknesses for maximizing LCF life will be calculated.

Second-Stage Nozzle

Ongoing analysis of the DOE results will be completed.

A second-phase DOE will be defined and executed for the purpose of carrying out Monte Carlo analysis, robust design studies, and life assessment of cast parts.

First-Stage Shroud

A second-phase DOE for performing robust design studies and developing response surfaces will be defined and executed.

Rotor Components

Robust design studies on the spoolie design will continue. In particular, a tolerance stack-up analysis will be performed to predict the distribution of interference fit, which can have a significant effect on stresses.

Turbine Inner Shell

3D mechanical DOE analysis will be performed, and response surfaces will be developed for active tip clearance control.

Technology Application

Results will be used in the development of part drawings in terms of nominal dimensions and manufacturing tolerances, LCF life assessment of as-cast parts to be received from vendors, quantifying the confidence level in meeting the CTQ requirements under various sources of variations, and improving part producibility by widening manufacturing tolerances.

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 began welding/fabrication to produce the first exhaust frame and diffusers. The machining and assembly drawing releases of the exhaust frame and

forward diffuser were completed. A cooling circuit analysis for power turndown operating conditions was completed. The 3D finite element analysis (FEA) of the exhaust frame and forward diffuser was completed for all mechanical and steady-state thermal effects as well as for transient thermal loads and stresses for final lifing estimates. The instrumentation modification machining drawing for design verification of the prototype exhaust frame with the forward diffuser will follow. A unit and exhaust structures assembly review was held in Greenville and at the supplier's site.

The aft diffuser duct completed internally-insulated "screening" tests (for performance impact) and showed promising results (for minimal performance impact) at CRD. Therefore, the outer aft diffuser will be combined with the diffuser duct (and will be internally insulated) for best cost advantage to the system. The 1/9-scale model for the exhaust inlet and mid-section (exhaust frame area) were ordered for testing in 3Q97.

Steam Gland

The machining and assembly releases of the steam gland were completed, and the vendor completed the casting and rough machining for the first unit. The geometry adjustments to the aft two seal designs—the "false flange" at top and bottom, etc.—were completed to ensure deflection and lifing concerns are met, and seal flows (for the reduced number of labyrinth seal teeth) were calculated. Machining drawings for the steam gland were issued. Detailed labyrinth seal drawings and all assembly component drawings were issued including modifications to reduce swirl interaction features. Instrumentation mod machining drawings for the prototype were issued.

#2 Bearing Housing

The casting vendor completed the casting for the first unit. Flow analysis of the oil and air seals was updated with the assumptions of holding rotor temperature and delta temperature across seals to within GE experience levels. The assembly and supporting seal and component drawings were issued. Transient thermal (machine trip) and flow analysis work will continue on the heat rejection at the bearing due to steam supply through the rotor bore and acceptable deflections. The prototype test instrumentation modification machining drawing was issued. Standard bearing instrumentation (for radial rotor vibration, bearing pad T/C's, and stator vibration sensors) as well as the prototype instrumentation assembly drawings were started.

Plans for Next Quarter

Exhaust Frame and Diffuser

The machining and assembly drawings of the 9H exhaust frame and forward diffuser, #2 bearing housing, and the steam gland are complete with focus shifting to instrumentation assembly releases and hardware first piece qualification (FPQ) inspections. The study of the total 9H diffuser flowpath with internal-insulation hangers will be started at CRD, and the final flowpath and predicted aerodynamic performance and acoustic interaction will be determined by 4Q97. Test of the steam pipes in the diffuser flowpath will be completed in 3Q97 or 4Q97 at CRD for a 1/9-scale model to properly model the effects of pipe vortex shedding and its possible effect on performance.

The exhaust frame and forward diffuser assembly will be completed at the vendor's site with only instrumentation lead-out remaining to be done.

Steam Gland

The prototype instrumentation assembly drawings will be issued and the vendor will have completed the machining FPQ. 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 #2 Bearing Housing instrumentation assembly drawings will be completed. The bearing housing machining vendor will complete the first unit. All interfacing conditions with the rotor, bearings, etc. will be established for off-design conditions (e.g., power turndown and machine trip).

Technology Application

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

Section 2.2.2.6.1 (GTFFSTEF) Vortex Shedding/Acoustic Test 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 flow path 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 flow path. 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 flow path, 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

A baseline scale model (using the current 9F flowpath model) exhaust diffuser reconfigured with internal surface strips to evaluate the effect of internal insulation on diffuser performance was instrumented for pressure recovery measurements. It was tested at both full speed, no load (FSNL) and full speed, full load (FSFL) conditions. The new ATS gas turbine 1/9-scale model was designed and the long lead time parts were ordered.

Plans for Next Quarter

A new scale model of the advanced gas turbine exhaust diffuser and exhaust duct will be constructed. It will be instrumented both for pressure recovery and for detection of acoustic resonances. Its performance will be mapped over a variety of inlet swirl angles and Mach numbers to verify that the design meets performance objectives.

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.

Progress for this Quarter

To confirm the results obtained thus far with NOVAK3D and to assess the effect of the constant exit static pressure assumption required by NOVAK3D, Tfc (another CFD code) was used to solve both the original and "continuous scroll outlet" concepts. Both Tfc and NOVAK predict a better performance for the modified design, as measured by the standard deviation of the velocity profiles about their mean. Although the comparison between the NOVAK and Tfc solutions is satisfactory, the root of the differences was investigated and found to be the differences in the flow predictions in the elbow region of the design. The NOVAK flow pattern indicates a stronger recirculation downstream of the elbow than predicted by Tfc. The effect of the exit static pressure on the solution was evaluated by running Tfc in the "uniform exit pressure" mode (similar to NOVAK's) and then again with the "non-uniform exit pressure" option. The results of this effort were documented and presented in a design review of the steam gland design. No outstanding issues in this area were identified. The proposed continuous scroll outlet concept is the current baseline design.

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

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

The maintainability, reliability, and serviceability team continues to work to ensure that all of the "lessons learned" for field operation are being incorporated into the 9H/7H design.

Performance estimates for both the 7H and 9H were updated, reflecting the current design configuration and assumptions. Machine cost data were updated as the designs matured, enabling more accurate estimates. System interfaces for the 9H were completed. Both 9H and 7H integrated schedules were updated to reflect current cycles and deliverables. A Risk Workout was held to update risk avoidance plans and accomplishments.

Plans for Next Quarter

System studies to optimize cost and performance will continue. Progress in cost, risk, schedule, and performance of the gas turbine design and manufacturing effort will be monitored and tracked. The component integration effort to establish and document interfaces will continue.

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 Platform Evaluation

Objective

The objective of this task is to evaluate computer platform and software options to best support the integration of a transient gas turbine model into a combined cycle simulation.

The current state of transient modeling for the ATS machine was reviewed with GEPG Engineering and was compared to the GEAE approach. From this brief study it was determined that a new transient model of the ATS machine was necessary in order to reflect more accurately its aero and thermal behavior. This work will assist GEPG Engineering in developing the new transient model with a steady-state accuracy goal of approximately $\pm 1\%$. The model will be designed to be included in overall power plant simulations.

Progress for This Quarter

The Fortran coding of a model to represent the time-temperature history of critical metal parts (heat soak model) was completed. The model currently operates in a stand-alone mode and will be integrated into the transient Cycle Deck in 3Q97. The required input data are being developed. The objective is to model the metal temperature of key metal parts and create a stress and clearance model for critical locations that uses the model metal temperatures. Several moderate steps were taken to speed up the transient cycle model, and calculations were extended to allow operation down to 5 rpm and zero fuel flow. The model is required to operate from startup to full load and at overspeed. Checkout of the transient cycle model over full operating range continues. A problem was identified in the speed range from 60 to 80% that requires further investigation into the stage-by-stage turbine map creation process.

Plans for Next Quarter

Preparation of data for the heat soak model will be completed and the model will be exercised and tuned; results will be compared to more detailed analysis to assure that metal temperature predictions are representative of key bulk metal temperatures. Stress and clearance models will be developed in 3Q97 and 4Q97 and added to the heat soak model. The gas turbine cycle model will be updated to represent current performance levels. Gas turbine startup torque and other key parameters predicted by the transient cycle model will be compared to startup torque calculations performed by an alternate, proven method. Modifications to the turbine representation in the transient cycle model will be undertaken if required.

Technology Application

This transient model will be used with detailed overall simulations of the plant gas and steam processes. This overall simulation will be used to verify the performance of the ATS system and to minimize the risk of any problems.

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

A preliminary design review of the 9H turbine base was held during 2Q97. No technical issues were found. The only open issue on the turbine base at this time is completion of the base-to-turbine interfaces. This issue will be addressed during 3Q97.

Preliminary design reviews were held for the air extraction, cooling air exhaust frame, clearance control, and cooled cooling-air piping. Several action items were generated for each with a plan put in place for implementation. Preliminary design for the balance of piping systems continued.

Plans for Next Quarter

A turbine base final design review is planned for 3Q97. System requirements will continue to be addressed and reviewed. Work on preliminary piping designs will continue, with final design reviews planned for cooling and sealing air, air extraction, cooling-air exhaust frame, clearance control, and cooled cooling-air piping systems.

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. These piping designs demand creative ideas in packaging and hardware selection.

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 telemetry system approach has been selected as a front end system for transmitting signals from all sensors mounted on the rotor including the compressor and turbine sections. The telemetry systems will be mounted in the load coupling. Work has started on the instrumentation drawings, including compressor rotor, turbine buckets, nozzles, and casings. The preliminary full speed, no load (FSNL) test plan has been prepared and provided to various engineering organizations for reviews and comments.

Plans for Next Quarter

The number of sensors required for the entire flange-to-flange gas turbine unit and power plant components for full speed, full load (FSFL) field test and the number of sensors to be

connected during FSNL factory test will be established. Work on the instrumentation drawings and telemetry system design will continue.

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) S1N 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

At the end of the entry tube the steam is turned through 90° and split from a single path to multiple paths. Complications encountered in the manufacture of this component required that the region be redesigned. This change caused a delay in the rig geometry mockup so that testing on this component did not begin as planned.

Pressure loss evaluations for the larger spoolies used in other areas of the flow system were completed, and the results matched well with the analytical assumptions and predictions.

Plans for Next Quarter

Flow tests of the entry tube 90° turn should begin after a new rig is built representing the revised geometry. Test results will be used to help characterize the flow losses and stability for the rotor steam system.

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 test 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

The new test rig was completed and installed, and shake-down tests were completed so that wear testing of larger spoolies at simulated engine operating conditions of temperature, pressure, G-field, and environment (steam) could take place. Preliminary testing in air successfully demonstrated the rig functionality and spoolie wear rates with the large spoolies that were consistent with the previous, successful small spoolie results.

Separate wear coating screening tests were completed for a number of candidate coatings, confirming the superiority of the selected production coating and identifying an additional wear/friction lubricant to further enhance wear performance.

Plans for Next Quarter

Several tests will begin to investigate wear rates in a steam and air environment, concentrating initially on the geometry effects of larger diameter spoolies

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

Because of machining problems on the duct mixing ribs that were resolved after several trials, four weeks were added to the initial estimate for completing duct construction and installation in the test rig by the end of 2Q97. The test duct machining was completed and its instrumentation is in progress. The successful machining technique consisted of completing the turbulators and ribs in each half of the duct, then welding them together with a graphite insert to prevent distortion. A conduction heat loss analysis has shown that, with only lead and trail-side heating, the wall conduction effect requires a different correction for thermocouple measurements when turbulators are present and when there are no turbulators. Since temperature measurements are required at both locations, the conduction analysis will be employed to obtain the correction factors for use in the data reduction code.

Plans for Next Quarter

The test duct will be installed in the test rig. Calibration tests will be performed. A test program is scheduled for completion at the end of 3Q97.

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

The computational fluid dynamics (CFD) part of this task was completed. The CFD results were summarized and documented in two formal CRD reports.

The model was refurbished during 2Q97 and the liquid crystals were replaced. The most recent set of tests was repeated to ensure repeatability of results. In this set of tests, the turn guide vane in the model was modified so that the ratio of passage areas on both sides of the turn guide vane matched the ratio of passage areas in the turbine bucket cooling circuit. Otherwise the model was identical to the model tested in 4Q96. Data reduction will be completed during 3Q97.

Experiments were planned to determine the effect of rotation on heat transfer in ducts of narrow cross-section (length-to-width ratio of 10:1), oriented at oblique angles to the axis of rotation. In the experiments, a high-molecular-weight gas (Refrigerant-134A) at ambient pressure and temperature conditions will be used to match the dimensionless parameters at engine conditions. Thin-foil heaters are used to produce a constant heat flux at the long sides of the duct; the narrow sides were unheated. Three duct cross-section orientations will be evaluated: 0°, 45°, and 60° to the axis of rotation. The test results will show the effect of rotation and orientation angle on duct leading and trailing side heat transfer. The test ducts

for the 0° and 45° configurations were constructed and instrumented. An existing rotating rig will be used for the testing. The rotating disk was modified for use with the test ducts.

Plans for Next Quarter

The results of the current liquid crystal test will be analyzed and compared to the initial test results.

Experiments will be conducted to determine the effect of rotation on heat transfer in ducts of narrow cross-section, oriented at oblique angles to the axis of rotation. The results of the experiments will be analyzed and forwarded to Design Engineering.

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. The data also 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.

Progress for this Quarter

Two series of heat transfer tests were conducted with the instrumented test section at two flowrates. The trailing edge holes were discharging to atmospheric pressure. The measured static pressure distributions agreed with the flow model predictions and showed a constant pressure all along the turbulated cavity that feeds the trailing edge holes. The calculated flowrates for both test pressure ratios were within 5% of the measured values.

The heat transfer tests were conducted by setting the flowrate and then setting the uniform heat flux to the thin-foil heater to a given value that started the color changes in the liquid crystal. Once steady state was reached, an image of the surface was recorded by the liquid crystal video thermography (LCVT) system for future analysis. The heat flux was then increased in preset steps and the surface temperature distributions were recorded for each case. Twelve images were recorded and saved for analysis. The liquid crystal color versus temperature calibration was performed in the calibrator. The surface temperature results with the known uniform heat flux values were then used to convert the data to heat transfer coefficient distribution data. The local heat transfer coefficients in the turbulated supply cavity and in the pin fin and turbulated trailing edge holes were measured.

Plans for Next Quarter

A report summarizing these results is being prepared and will be submitted to GE Power Systems.

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.

Progress for this Quarter

A series of tests was conducted to investigate the effect of the distance between the jet plate and the impingement test plate (Z/D) on the jet flowrate for a given constant pressure ratio. The results showed that for a given pressure ratio, the flowrate increases and reaches an asymptotic value as the distance between the plates increases. The impingement program developed for the design calculations appears to calculate the correct flowrates as long as the jet-to-plate distance (Z/D) is greater than 0.75.

In another series of tests, the impingement test plate was instrumented with a liquid crystal and a thin-foil heater. In addition to the impingement heat transfer coefficients distribution, the static pressure distributions were also measured along the side wall at the jet injection locations and in between jets. These tests were conducted with the first row of jets impinging

near a wall with a zero velocity boundary condition. The static pressure and impingement heat transfer coefficients are being compared with the correlations and model calculations.

Plans for Next Quarter

The static pressure and impingement heat transfer coefficient distributions measured in the two series of tests will be compared and analyzed. The test section will be modified to accommodate cross flow discharging symmetrically in two directions rather than one direction as in the test results reported.

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 the typical cast components.

The objective of the flow checks, conducted with air, is to check the flowrates and static pressure distributions of two 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 be conducted at GEPS to ensure that every component fulfills the flow design requirements.

Progress for this Quarter

The first-stage nozzle cast vane appeared to have some porosity in the vane side ribs separating cavity 2 from cavities 1 and 3. Preliminary tests to determine whether cast porous ribs leak coolant from one cavity to another were conducted by pressurizing one cavity and checking for leakage into the neighboring cavities. The test results showed that there were no leaks between the cavities through the separating rib walls.

Plans for Next Quarter

The necessary flow tests and static pressure distribution measurements will be performed as the cast nozzle and bucket components are available from the manufacturer.

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 applied easily and polished to uniform thickness and surface finish. Full mapping of the TBC surface topography will be performed. Reynolds numbers will span those expected in the ATS turbine inlet nozzle surface away from the leading edge. Verification tests on airfoil replicas will be performed.

Progress for this Quarter

The test rig has been fully assembled and checked for safety requirements. All six instrumented test plates were received from the vendor. Heat flux gauge calibrations were completed for the first three test plates. Infrared emissivity calibration was performed for the smooth, metallic baseline plate.

Plans for Next Quarter

Heat transfer tests will be performed on as-sprayed TBC surfaces and the baseline smooth plate (no TBC) without steps.

Technology Application

The results will help determine what surface finish is allowable for the airfoil TBCs.

Section 2.2.3.6.1 (GTETEH) SIN 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 was examined to determine whether the E-beam unit can simulate the metal thermal environment expected in the fillet regions of the first-stage nozzle. The specimen was coated with a coating that was found in previous tests to be a good qualitative guide to the location and magnitude of the strain pattern developed in the specimen. This particular specimen was instrumented with several type-K thermocouples. No strain gauges were included in the instrumentation because in the pre-experiment analysis there were no locations on the specimen that were cool enough for the strain gauges to survive and also remain sensitive to the strain state in the fillet.

The thermal gradient through this specimen was established in the same way as in our previous tests (i.e., with an array of impingement jets of helium). Because of the presence of the fillet, the impingement nozzle also had to have a fillet-like geometry. Several patterns and sizes of cooling holes were tested. The goal of these tests was to try to smooth out the surface temperature of the metal at the lips of the fillet. A decision was made to use a nozzle geometry with 50-mil holes on the flat section and first row on the fillet wall section and 15-mil holes elsewhere in the fillet region. A change was made in the geometry of the copper cooling plate that protects the instrumentation and specimen holder from reaching too high a temperature. The aperture of this plate has been enlarged to allow the walls of the fillet specimen to heat up more than those of a regular tophat. The predictive stress analysis performed before this test was run indicated the need for this feature.

Prior experience with coated tophat specimens suggests that cracking in the coating layer should be expected after 200 cycles. The cracking becomes visible in a dye penetrant test.

Fifty cycles have been run on the specimen with no cracking observable by dye penetrant. Further cycling of the specimen is underway.

Plans for Next Quarter

The stress field investigation using the coated specimen will be completed. Results from the metallurgical examination of the previous specimens will be summarized.

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 results from ATS Phase 2 studies.

Progress for this Quarter

Static Specimen Results

The static specimens, impingement and turbulated, installed in 1996 were on-line for 31 and 38 weeks, respectively, with few outages. The specimens were again taken off-line at the end of 1Q97, when the steam system to which they were connected was shut down for a 7-year overhaul.

During 2Q97 the specimens were examined by borescope and sampled using remote manipulators in order to leave the specimens available for further exposure and to avoid disturbing any deposits as much as possible. The borescope analyses were recorded to videotape, and any removable deposits were analyzed for Cr, Mo, and Fe, since the plant superheater tubes were 2.25Cr, 1Mo, balance Fe.

The *impingement* specimen (portion of first-stage nozzle cooling) was very clean with no removable deposit observed at all. Only a slight darkening of the target wall adjacent to the distributor holes showed any relationship between the holes and the adjacent wall, and that slight darkening was approximately the same diameter as the holes and was not removable.

The *convection* specimen showed a thin, spotty deposit that was less dense between turbulator dams but did not build up heavily in any area. Samples of the deposit were removed and an enrichment in the Cr and Mo alloying elements indicated that the material had come from the plant superheater tubes. A deposit of less than 50 micrograms was collected from between two dams, which would translate into an acceptable buildup rate. Further sampling will be done in 3Q97 to characterize the physical makeup of the deposit, including particle sizes and shapes of the particles to determine whether gravitational fields might concentrate material in the tip region.

Plans for Next Quarter

A second area sampling will be conducted, and the bucket deposit will be analyzed further to determine the physical character of the deposit. A project review will be held and a final decision will then be made on the need to conduct the rotational experiments. The centrifuge will be disassembled and prepared for a leakage test of new ATS gas turbine steam seals as part of the CRD Steam Gland Brush Seals task reported on in Section 2.2.4.14.2. If the brush seals perform well, it is likely that any further trials with the centrifuge will be made using brush seals in place of the "non-contacting" carbon seals that have not worked in trials to-date. In addition, experience gained on the ATS steam deposition program will be transitioned by contributing to task force technology discussions involving (1) steam cooling system reliability and (2) specification of instrumentation required for reliable operation and diagnosis of the prototype ATS power plant.

Technology Application

Data from tests under this steam particulate deposition task will allow for the necessary steam filter specifications to be established. 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.

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

An internal interim report was issued that documents a disk and wheel lifing criterion based on smooth bar low cycle fatigue (LCF) test results collected on IN718 for this program. A number of mechanical property behavior curves were assembled for IN718 and prepared for official communication to Design Engineering. Fatigue crack growth rate (FCGR) testing of the first piece qualification (FPQ) turbine wheel material was initiated. Optical microscopy,

scanning electron microscopy (SEM), transmission electron microscopy (TEM), and auger analysis continued to be used to examine the fracture surfaces of the various test specimens.

Work continued on studying the effect of environmental conditions on the welded and brazed joints that will be used with the hot gas path materials. Slow strain rate tests (SSRT) were used to discriminate between various joint processing options. Test matrices to provide Handbook data were completed. Construction of test specimens was initiated where sample material was available. Additional material to support test specimen fabrication was expedited from the investment casting foundries.

SSRT tests were conducted with the rotor steam delivery materials to permit discrimination between various manufacturing process options. Optimum conditions were identified. Testing in steam was impeded by some test rig issues. Modification of the test specimen permitted collection of an initial sampling of LCF data.

Various types of mechanical test specimens for the hot gas path materials were machined. They included 34 crack growth, 14 creep, and 6 LCF specimens for the second-stage bucket material; 16 crack growth, 4 creep, and 10 LCF specimens for the first-stage bucket material; and 12 crack growth, 6 creep, and 13 LCF specimens for the second-stage nozzle material. The LCF specimens made from the first-stage bucket material were machined from cast slabs intentionally produced with casting defects.

Plans for Next Quarter

Steam dynamic crack growth rate threshold testing of another sample of IN718 designated "Ingot 4" will be started. Fabrication of high priority welded and brazed joints to permit characterization of mechanical properties for construction of Handbook curves for hot gas path materials will be continued. LCF and creep testing of these hot gas path material specimens in steam will be started. LCF testing of rotor steam delivery material specimens will be continued. Additional cast slabs of hot gas path materials will be obtained. Machining of these slabs into additional LCF, crack growth, and creep specimens will be started.

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.

Progress for this Quarter

Earlier results from steam oxidation tests were found to provide an adequate description of material behavior. These tests were suspended during this reporting period.

Plans for Next Quarter

This task has been completed.

Technology Application

This task will 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 additional hours of exposure time were accumulated on those coated samples still running in the high-temperature oxidation burner rigs. 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

Strain-to-crack testing at various temperatures on all coating compositions of interest will be completed. The 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.

Progress for this Quarter

This task has been completed.

Plans for Next Quarter

No future work is planned for this activity.

Technology Application

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

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

Information to support selection of materials for the variable guide vane (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.

Progress for this Quarter

The candidate bushing and washer materials completed the impact tests and oscillating wear tests. A report was written and the results were discussed with Design Engineering.

Plans for Next Quarter

This task has been completed.

Technology Application

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

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

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

Progress for this Quarter

High cycle fatigue (HCF) testing of one of the compressor rotor wheel materials continued at two different temperatures. Smooth and notched bar tests were conducted at two mean stress levels. GE continued technical support of the diffuser supplier to address manufacturing issues that were discovered during the casting of the prototype diffuser.

Plans for Next Quarter

Collection of HCF data for the remaining wheel material in test will continue. When the tests are completed, the data will be analyzed and the results reported to Design Engineering. The diffuser casting supplier's Manufacturing Process Plan (MPP) will be completed and the parts will be subjected to first piece qualification (FPQ) testing.

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

GE ultrasonic evaluation of the rotor forgings was completed. Work was initiated to correlate the ultrasound results to specific features in the forgings. Analysis of these test results and subsequent disposition of each of the forgings was begun. Sensitivity studies on the machining of the wheel material were completed. Analysis of the results was begun.

Smooth bar low cycle fatigue (LCF) tests with two hold times and at two different temperatures continued. Handbook curves for LCF tests conducted earlier were issued to Design Engineering. Additional creep, tensile, crack growth rate, and static and dynamic crack growth rate tests were conducted on samples of the wheel material that were taken from various forgings.

Plans for Next Quarter

Final disposition of all the rotor forgings will be made. The correlation of ultrasound results to features in the forgings will be documented. The optimized machining parameters will be implemented. 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 pending 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

Machining of sheet specimens intended for tubing material property evaluation was completed. Tensile, creep, and fatigue specimens for both the parent and welded material were machined. Sheet specimens for spoolie material property evaluation were obtained from the spoolie vendor and were also machined. Tensile testing of tubes was completed. The results confirmed earlier work conducted on sheet specimens. An evaluation of various surface treatments to enhance the properties of the steam delivery tubes was completed. The tests highlighted the incremental benefit that could be obtained with each of these treatments. The results will be used to fine tune the manufacturing processes for these parts.

Manufacturing Process Plans (MPPs) were reviewed for the various rotor steam delivery components. Comments were forwarded to the suppliers and the processes are being refined. New part specifications were written for several components.

Block-on-shoe wear testing of eleven candidate spoolie coating systems was completed. Initial shakedown testing was completed in an air environment. Eleven coating systems were tested in conditions representative of the planned operating environment. Good performers in this group exhibited a significant reduction in the frictional forces in the first 10,000 cycles of the test. They also had well-developed wear scars and little galling. Poor performers had frictional forces as high as the uncoated base metal. The top five performing coating systems from this initial screening test were tested in more rigorous conditions to permit discrimination of the wear behavior. In this second round of tests, only two coating systems were able to reduce the frictional forces throughout the course of the test. As a result of this work, these two materials were selected to reduce friction and wear in the rotor steam delivery system. Material and process specifications were issued for these materials.

Plans for Next Quarter

Mechanical property spot checks will be conducted on production parts to ensure that the final processing of the material provides the properties that were developed in laboratory trials. Metallurgical evaluation of the spoolies, representative of various processing options, will continue. Testing of sheet material used for the spoolies, steam tubes, and manifolds will also continue. Welds used in the fabrication of the steam cooling circuitry will be evaluated. Initial baseline tests will be conducted in air in the wear test rig to enhance understanding of the interaction of adjacent materials. Steam testing will then be initiated to monitor the

behavior of these interfaces in service condition environments. Additional MPPs will be reviewed, and suppliers will be supported in the manufacture of hardware.

The fretting resistance of the top performing coating systems will be investigated. Results of these tests will be used for life prediction of the wear coating for the rotor steam delivery system. Work will also begin to qualify suppliers for the application of these wear reduction materials.

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 were started on additional heats of three different bolting materials. The remaining tests are to be loaded during this reporting period. Additional baseline material was ordered for the relaxation program. The influence of pre-conditioning on the subsequent stress relaxation response of one of the compressor bolting materials is also being investigated.

Plans for Next Quarter

Collection of long-term relaxation data will be continued 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

Additional low cycle fatigue (LCF) tests on first-stage bucket material containing casting defects were conducted at five selected temperatures. Creep and high cycle fatigue (HCF) tests on first-stage bucket material containing casting defects were conducted at one selected temperature. The defect types tested included low- and high-angle boundaries. Recently, LCF tests were initiated on second-stage bucket material with casting defects, and these tests are continuing. The defect types being evaluated in this material include emergent grains and misoriented grains.

Tensile, creep, and LCF tests were initiated on the third-stage nozzle material at various temperatures and stresses. These tests are part of a full-scale design data program that includes various physical properties, oxidation and hot corrosion, and crack growth. Additional cast slabs of this material were ordered.

Preliminary design curves were issued for first-stage and second-stage bucket materials with defects.

Plans for Next Quarter

Additional LCF tests on defect-containing first- and second-stage bucket material will be conducted. Creep and LCF tests on the third-stage nozzle material will continue. Long-term creep tests on various bucket and nozzle alloys will continue. Test material to support the evaluation of welded and brazed airfoil joints will be obtained. Standard specimens for testing will be made and some tests will be run.

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

Discussions were held with Design Engineering to determine test needs. A test matrix for evaluation of sheet material with tensile, creep, and low cycle fatigue (LCF) of welded structures was agreed upon. Two materials were selected for evaluation. The master ingot of one material was melted and hot rolled into sheet stock. A sample of an alternative sheet material was ordered to permit a one-to-one comparison.

Plans for Next Quarter

Machining and testing suppliers will be selected. Material shipment is expected early in 4Q97.

Technology Application

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

Section 2.2.4.12 (GTMTST) Turbine Structures Materials and Processes

Objective

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

Progress for this Quarter

Following reviews with potential suppliers, the process selection for the steam manifold adapter castings was resolved. Design Engineering was advised on process capabilities. The part will be manufactured as an investment casting. Creation of a new part specification to define necessary acceptance criteria for the torque shaft was initiated. All outstanding issues related to process, establishment of acceptance requirements, and qualification requirements were resolved. Drawings for the third-stage diaphragm machining, third-stage inducer machining, and fourth-stage shroud were reviewed and approved. For each manifold segment, the supplier produced three to four investment castings with different gating concepts. The results were reviewed with the supplier and the team selected the optimum process. The part specification for the manifold was revised.

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

A Manufacturing Process Plan (MPP) was reviewed for the inner turbine shell. The supplier welded two ring forgings in support of this component.

Plans for Next Quarter

The final weld and inspection plans from the supplier will be reviewed and a determination made as to the need for additional development work.

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.

Progress for this Quarter

All metallurgical work on this activity has been completed.

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 (GTFFTSSSESV) 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. The objective of this task is to develop and test cloth 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 objective of this task is to 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

Inner and outer cloth seals were fabricated for use in full speed, no load (FSNL) tests and for leakage and low cycle fatigue (LCF) evaluations at CRD. A number of cloth side seal design concepts are being fabricated for further evaluation. The issue of installation (i.e., access) is being addressed. Jaw design for LCF testing was completed. The high-temperature oven for LCF testing was designed.

Transition Piece Cloth Seals

Leakage performance tests of seal junctions under a range of pressure, offset, and skew (misalignment) conditions are progressing well. The seal junction tests included straight, two-piece corners, single-piece with 0.5-inch radius, and single piece with 1.0-inch radius. Test results show that the leakage rate is different for each of the four designs. The 0.5-inch radius seal was selected for slot configuration design based on leakage performance and manufacturability.

Plans for Next Quarter

Hot Gas Path Cloth Seals

Fabrication of the high-temperature oven for LCF testing and jaws for testing seal functions will begin.

Transition Piece Cloth Seals

High-temperature material oxidation tests on L605, HS188, and IN750 wire and sheet stock will be performed.

Technology Application

Cloth seal design concepts developed thus far are being designed as specific components for the ATS gas turbine. More tests are underway to determine design attributes that influence their application in practice: seal assembly, tolerances, and sensitivity to slot geometry.

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

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of the two-stage seal. Wear is assumed to occur mostly during transients, therefore 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 dynamic leakage testing is to measure seal leakage during rotation and to determine the durability of the two-stage seal design in a high-pressure steam environment. During this reporting period the brush seals, seal holder, and test rig rotor were being manufactured. All the test hardware will be delivered at the beginning of 3Q97. A detailed test plan was prepared and instrumentation for the test was ordered.

Plans for Next Quarter

The dynamic leakage test will be conducted and the durability of the seal design will be verified. Wear data from the brush seal will be obtained.

Technology Application

The brush seals will be used in the first machine by nesting the brush seal in 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

Efforts continue to examine the repair of single crystal alloys.

Plans for Next Quarter

Studies will continue to evaluate repair methods for single crystal alloys.

Technology Application

The ability to repair airfoils will result in more cost-effective flow path 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.

Progress for this Quarter

Robot Motion Control and Part 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) are being fully evaluated to assure matched performance. The evaluations were delayed until later in the year due to ongoing development of ROBCAD software utilities for the FANUC Robotics product called Segment Time Programming (STP) as well as development of improved test parts.

An ATS nozzle replica, fixture, and turntable platen were developed to support development of motion control and path programming techniques. The nozzle replica was enhanced to permit evaluation of various motion control strategies. Precision laser targets were developed and tested for measuring velocities on buckets and nozzles. The current design works well for both airfoils and platforms; however, additional development may be required to accurately measure velocities in the fillets.

ATS bucket replica airfoils and fixturing were designed and drawings prepared. Three types of airfoils were designed: one for surface velocity measurements, one with internal cavities to simulate an actual bucket, and one solid bucket to determine how thermal mass affects coating quality.

Two approaches for inverse time motion programming are being developed. The first is STP. STP motion development and programming techniques are initially focused on "Patch Motion" in support of the first set of ATS hardware. A set of progressive experiments was designed, beginning with constant velocity tests and leading to a series of variable velocity tests. Constant velocity trials are underway. Additionally, testing and installation of three new software modules aimed at decreasing the amount of time necessary to create a part program were completed. Development of the last module needed to upgrade the software used to program the robot controller was also completed.

The second programming approach is through Coordination through Short Motion Programming (CSMP), a custom product being developed by CRD. The newest approach integrates advanced CSMP path planning techniques with FANUC Robotics Karel/STP programming. The CSMP model incorporates the measured performance limits for the M710i/RJ2 robot system, including motion dynamics for each axis (position, velocity, and acceleration limits). The M710i/RJ2 robot system is performing very systematically and gives excellent agreement with the CSMP model.

All CSMP testing has focused on the more demanding "Continuous Motion" approach using the enhanced ATS Nozzle Replica System. Both optimized path acceleration and robot/part motion synchronization testing have been performed. Path accuracy during Constant Velocity trials has significantly exceeded requirements. Variable Velocity trials have begun.

Coating trials on pre-production hardware continued to determine the best approaches for the first sets of ATS hardware. A decision was made on a motion approach for nozzles. Three approaches were tried, and the one that gave the lowest standard deviation on thickness while still meeting the nominal target was chosen. The thickness data are now being examined in more detail to determine where further improvements can be made. Improvements in coating quality recently made on buckets, by adjusting both robotic and non-robotic parameters, will also be incorporated into the nozzle motions and processes.

TBC Process Development for Transition Pieces

An ATS transition piece to be used for combustion testing later in the year was coated in the production spray cell. The TBC process used was a refinement of a process developed by GE Aircraft Engines for axisymmetric components. Funding of TBC development for transition pieces was subsequently transferred from the ATS program to an internal program in order to focus more resources toward refinement of the TBC processes for airfoils.

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

A new gun tooling system was developed to provide precise and repeatable gun mounting. The CAD/CAM design was completed, and prototype testing was performed and approved. The gun tooling systems were installed in the three airfoil spray cells. Evaluations and calibrations of non-robotic booth equipment are being performed to assure equivalency between sites. Coating sample plates were sprayed at three GE sites using the spray practices in place at each site prior to the standardization of the spray practices. Measurement of coating mechanical properties began.

Further work has been done to establish the choices for the standard spray practices. Review of past designed experiments showed that a slight reduction in the carrier gas flow used when applying ceramic top coats was warranted. This change was made to the standard practice.

Some powder injector plugging problems were seen at one site with this reduced carrier gas flow. Changes to the software for the plasma gas control system are being investigated; these changes should reduce or eliminate the injector plugging.

Additional trial airfoils were provided to vendors for evaluation of surface finishing capability. One technique, which utilizes part-specific soft tooling and conformable abrasive media, showed good initial results. Work to identify the proper profilometer settings for measurement of final TBC surface finish was completed. Two sets of calibration plates were created at various TBC finishes, ranging from as-sprayed to fully finished. These were evaluated by the profilometer manufacturer, and recommended profilometer settings and measured surface finish were provided.

TBC Process and Diagnostics

Information for various plasma guns was accumulated and suggested process conditions were obtained from the gun vendors. Experiments were begun to evaluate coatings sprayed using three alternate guns.

Preliminary evaluations of a new plasma mini-gun, which may be needed to coat the welded joint for second-stage nozzle doublets, were performed. The gun showed capability for achieving good TBC microstructures with high reliability and low maintenance.

Methods for surface preparation prior to performing local air plasma spray (APS) repairs to as-processed TBCs were evaluated.

A protocol for measuring preheat and deposition temperature will be specified using the Inframetrics IN760 Infra-Red (IR) thermal imager. Good agreement was observed between IR temperature measurements and thermocouples attached to production buckets. Data acquisition software was obtained. Development of several types of calibration specimens for determining TBC surface temperature was begun.

Evaluation of the gas-fired auxiliary heating source in the production spray cell showed significant improvement in part temperature control over plasma gun preheating alone. Strategies to control the gas torches, as well as use the gas torches in conjunction with the plasma gun, were evaluated.

Nondestructive TBC Thickness Measurement

Development of an automated hybrid top coat thickness measurement system using a flexible eddy current probe in combination with a multi-axis scanner is nearly complete. Installed coordinate measuring machines (CMMs) in Schenectady and Greenville will be used as the scanning devices. The other elements of the system include a redesigned eddy current probe and 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. Installation and checkout of the Mark 1 system will be completed in 3Q97.

Nondestructive TBC Evaluation

A program to apply laser ultrasonics for nondestructive evaluation of TBC elastic (Young's) moduli was begun. Current techniques use mechanical resonance to extract the coating modulus indirectly. 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 which predominantly propagates in the coating. A laser interferometer senses the Angstrom-amplitude propagating wave signal, which is stored on a computer and analyzed for frequency dispersion content. With the coating thickness known, the Young's modulus can be calculated once an analytic model of the system has been constructed.

The coatings contain anisotropy (e.g., in-plane versus through-thickness) and are not adequately described by a single number. Inversion tools for extracting all relevant moduli are under development, and a cooperative agreement for study of this problem has been worked out with CNRC/IMI (Canadian National Research Council). A numerical model for calculation of dispersion properties from mechanical constants was developed. This model indicates that dispersion properties are sensitive to coating mechanical properties and not to the bond line. In addition, preliminary laser ultrasound data were acquired for an existing set of samples that produce results consistent with our model and with mechanical resonance measurements. A new approach for extracting complete multiple mode dispersion curves was developed.

Plans for Next Quarter

Robot Motion Control and Part Programming Methods for Airfoils

Robot motion equivalency tests at each site using the enhanced 9H Nozzle Replica, gun tooling, and ROBCAD/STP programming tools will be completed. The Visible Laser System in motion development experiments will be applied at one site (Beta test). Laser Target development and testing for measuring robot motion performance on 9H buckets and nozzles will continue.

STP development using "Patch Motion" with constant and variable velocity will continue. CSMP development using Continuous Motion with variable velocity will continue. Plans for ROBCAD/CSMP Integration will be established and development of a Software Design Specification will begin.

Coating quality on buckets and nozzles for the first set of ATS hardware will be further optimized. Initial bucket replica tests will be performed.

TBC Manufacturing Technologies

Booth equivalency tests at three GE airfoil coating facilities will be completed. A manufacturing upgrade to production status—including masking, instrumentation, machining, and coating parameter activities—will be supported.

TBC Process and Diagnostics

Evaluations of various plasma guns will be continued. Experiments to evaluate APS repair of an as-processed TBC will be completed. Automated temperature acquisition for the IN760 will be developed. IN760 will be calibrated for the effect of ceramic translucency.

Nondestructive TBC Thickness Measurement

Installation of the automated Mark 1 eddy current ceramic coating thickness scanner will be completed. Metallographic measurements of bond coat thickness on specimens with eddy current measurements will be correlated using the flexible probe system.

Nondestructive TBC Evaluation

Laser ultrasonic data for a family of coatings will be acquired. Analysis will be performed to produce an in-plane modulus similar to the modulus obtained with existing mechanical resonance techniques. Complete dispersion relations will be measured for comparison with theoretical models. Elastic tensor measurement experiments for a family of samples will be completed in cooperation with CNRC/IMI.

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

Testing of a flat tophat pre-aged using long-hold furnace exposure is complete; 2500 cycles were accumulated at full ATS conditions with no apparent TBC damage.

A PtAl-coated fillet tophat was tested under moderate conditions to produce tophat stress and temperature maps. This information is needed to determine instrument locations for full-condition testing.

Plans for Next Quarter

All further work is deferred until next year to correlate funding and design development requirements.

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 (1037-1093°C, 1900-2000°F), and incorporating the results into an existing cumulative damage model. In support of this modeling approach, microstructural features of the bond coat and ceramic top coat will also be examined.

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

The spatial and run-to-run variability of TBC thermal conductivity will be evaluated. Improved understanding of this variability is essential because the variation in TBC thermal conductivity can be several times greater than that seen in metals due to variations in TBC microstructure, leading to design inaccuracy. 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.

Information from this task will be used as input to other tasks. Appropriate data and modeling results from parallel GE programs will be incorporated. Design guidelines will be developed for TBCs on ATS components. Ultimately, a TBC life analysis methodology and a life predictive model will be developed. These will include effects of long-term exposure on top coat and bond coat physical and mechanical properties.

Progress for this Quarter

Furnace Cycle Test

Porous and dense vertically-cracked (DVC) TBC specimens are being furnace cycled at 1093°C (2000°F) using dwell times of 0.1, 0.75, and 10 hours per cycle. No differences in life between the porous and DVC TBCs were observed at dwell times of 0.75 and 10 hours. Differences in failure modes for the various temperatures and dwell times were observed.

Thermal Conductivity

The primary objective in 1997 is to produce refined design data for TBC thermal conductivity as functions of temperature and aging time. The three furnaces needed to conduct aging to at least 1000 hours were profiled using calibrated thermocouples. The temperatures in the region for sample placement are uniform to $\pm 1^\circ\text{C}$. Enhancements were made to the furnaces for improved reliability.

A trial aging run was performed. Polished and unpolished samples were aged at 1366°C (2491°F) for 2 days. Sample distortions were too large to be corrected by subsequent polishing. As a result, polished samples will be used for future aging runs.

Free-standing TBC samples (12-mm diameter) were prepared, including grinding both sides flat and smooth. Some of these samples are being aged in air for 1000 hours at 1038, 1204, and 1316°C (1900, 2200, and 2400°F). These samples will be compared with corresponding samples aged for short times (i.e., <100 hours).

Plans for Next Quarter

Testing of porous and DVC TBCs at 1093°C (2000°F) using dwell times of 0.1, 0.75, and 10 hours/cycle will be completed. Testing at 1093°C (2000°F) using a dwell time of 20 hours/cycle will begin after a revised test specification has been transferred to the test vendor. Testing at 1037°C (1900°F) using dwell times of 0.1, 0.75, and 10 hours/cycle will begin. This testing will extend beyond 1997, at which point the data will be incorporated into a TBC lifing model.

Thickness and density measurements will be performed on aged samples. Thermal diffusivity measurements of aged and unaged samples will be performed at ORNL.

Technology Application

A database will be established that will link TBC properties and durability in laboratory tests to TBC durability in the ATS turbine. Ultimately this database will be used 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 ATS turbine employs a DLN 2.6 combustion system that requires the gas fuel to be heated in order to achieve the overall ATS efficiency goal. The cooling-air cooling system is required to maintain temperature in 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 turbine. The clearance control system 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.

Design of the heat exchanger and piping for the hot fuel will take into consideration the need to avoid coking. Deposit formation will be investigated. The effectiveness of coke barrier coatings, which have been under development for liquid-fueled systems, will be evaluated in long-term tests.

Progress for this Quarter

Cooling-Air Cooling System

In 1Q97, as a result of a cooling-air cooling (CAC) system feasibility study, the configuration was changed from a high-pressure (HP) system to an intermediate-pressure (IP) system. This change resulted in several component level changes to the system that reduced the cost significantly. During 2Q97 this type of change continued. A material change from stainless steel to CrMoV for the heat exchanger vessel and the valve bodies was agreed upon, reducing the cost of those components. In addition, another cost reduction was realized when it was determined that filtering to the 50-micron level was unnecessary, and that a 40 mesh strainer

would provide adequate cleanup of the cooling air. With these system configuration changes complete, the preliminary system P&ID was created, reviewed, and issued. A preliminary system functional specification was also created and issued.

Steam Cooling System

Changes were made to the design requirements for the steam cooling flow that affected the preliminary design of the steam cooling system components. In addition, preliminary outline drawings for the steam cooling system components (the steam filter vessel, the steam cooling valves, and the steam flow meter) were developed and issued. These outline drawings will provide the steam cooling system suppliers with the information required to develop the detailed design of these components.

Clearance Control System

The design memo book was updated with the new design requirements for the clearance control system (CCS) that were established during 1Q97. With those changes in place and documented, the preliminary system P&ID and system functional specification were created, reviewed, and issued. Using these documents in working with suppliers, cost reductions were realized as a result of the design changes made in 1Q97.

Plans for Next Quarter

Fuel Heating System

The engineering design team will select suppliers and begin to develop the detailed design of the various gas fuel heating system components with those suppliers. As the components are developed, the final functional specification will be written and released. In addition, the failure modes and effects analysis (FMEA) for the gas fuel heating system will be developed further.

Cooling-Air Cooling System

With the preliminary functional specification and P&ID completed for the CAC system, the detailed design of the CAC system components will be developed. This development will also include several internal design reviews as well as supplier reviews. In addition, the FMEA for the CAC system will be developed further.

Steam Cooling System

The detailed design of the steam cooling system components will continue to be defined by the engineering design team and its suppliers based on the changes to the design requirements made in 2Q97 and the outline drawing issued in 2Q97. In addition, the FMEA for the steam cooling system will be developed further.

Clearance Control System

With the preliminary functional specification and P&ID completed for the CCS, the detailed design of the CCS components will be developed. This development will also include several internal design reviews as well as supplier reviews. In addition, the FMEA for the CCS will be developed further.

Technology Application

Development of the fuel heating system, 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 system models were developed and are being used in an ongoing study of the dynamics of the combined cycle, the combined cycle components, and the control system. The control sequences for startup and shutdown were studied, including efforts to develop valve transition logic for management of air and steam flows to the gas turbine. Other control loop dynamic studies are also being studied. Work continues to develop the algorithms for control and protection of the ATS gas turbine. In the development of an integrated control system, the manufacturing processes for the first prototype control panels are underway.

Plans for Next Quarter

Study of control loop dynamics will continue. Software algorithms will be defined for gas turbine, steam turbine, and HRSG controls. Software algorithms and sequence logic will be defined for auxiliary systems. Verification of the control algorithms, using equipment models and actual control panels, will begin. Manufacture of the first prototype panels will be completed and prototype tests will begin.

Technology Application

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

Section 2.3.3 (CCRA) Reliability, Availability, and Maintainability (RAM) Analysis

Objective

An evaluation of the reliability, availability, and maintainability (RAM) of the 7H equipment will be performed. The basis for the work will be the 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 reporting period has been restricted to FMEAs.

Gas Turbine Flange-to-Flange - Turbine and Compressor

FMEA development continued on all unconventional aspects of the turbine and compressor. Over 50 FMEAs were identified to-date in Gas Turbine Flange-to-Flange. The following systems were completed: steam gland; third-stage bucket cooling delivery; exhaust frame cooling systems Nos. 1 and 2; steam delivery bore tube; compressor rotor/cooling; variable guide vane (VGV) components; outer turbine shell arrangement; and outer turbine shell. The following systems were partially completed (10% to 90%): first-, second-, third-, and fourth-stage bucket castings; inner shell and clearance control; steam piping; first- and second-stage shrouds, second-, third-, and fourth-stage nozzle castings; Greenville generic piping; cross tubes, supply cross tubes, manifold cover plate, return cross tubes, aft shaft windage cover, and manifold spring for steam delivery; first-stage nozzle support ring; and Greenville turbine base.

Plans for Next Quarter

FMEA development will continue on the following: turbine stator system; turbine buckets; compressor; combustion; stator structures; steam delivery system; 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

Analysis will be performed and the combined cycle system will be configured to optimize 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 develop and validate control system design, and assess component design. Operability will be assessed.

Progress for this Quarter

The steady-state performance model (SSPM) for the STAG 109H was updated to include optimized design of the cooling-air cooling system and gas fuel heating system. The 9H gas turbine Cycle Deck was updated and incorporated an updated steam bottoming cycle model into the SSPM. Extension of both the STAG 109H and 107H SSPMs to include automation of design point calculations continued. The 9H rotor clearance control (CC) system was studied and optimized. Definition of machine operating limits for use in STAG 109H system

design and implementation into the control system are on schedule for the full speed, no load (FSNL) test. Hot Restart and Load Change transients were successfully evaluated using the thermal dynamic model (TDM). TDM results and findings were incorporated into FMEA analysis for transient behavior of H-machine-specific new systems, which include: gas turbine steam cooling, cooling-air cooling, and gas fuel heating systems. Initial work was performed on the TDM to upgrade it to a higher fidelity gas turbine model.

Plans for Next Quarter

Extension of both the STAG 109H and 107H SSPMs to include automation of design point calculations will continue. Work will continue on machine operating limits and control strategy definition for use in the 9H gas turbine prototype. Design Standards and Guidelines Documentation will be generated for use by CC Applications Engineering. Three process improvement projects have begun and will be worked on through the end of 4Q97. The target for these quality projects are both the SSPM and the TDM. The TDM upgrade to a higher fidelity gas turbine model will continue.

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. Manufacturing schedules will be established to support ATS pre-commercial demonstration goals. Manufacturing schedules and cost will be defined.

Progress for this Quarter

Forging operations were completed on the IN718 turbine rotor forgings, which were shipped to the machining supplier for inspection and machining. TBC process qualifications for H-machine airfoil coating continued and the Greenville, SC, coating facility became operational for airfoil components. Significant progress was made on establishing a full speed, no load (FSNL) test stand design. Site work was started and the necessary permits are being obtained.

Plans for Next Quarter

The IN718 forgings will be machined for delivery to the Greenville, SC, coating facility. TBC process qualification will be completed for airfoil components. Components for the FSNL test stand will be ordered and construction of the test stand will begin.

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 NO_x emissions will be identified. Analyses will be run to optimize the integration of the steam cycle with one oxygen-blown entrained flow gasifier and gas cleanup system and integration of the gas turbine with the air separation unit. IGCC system performance will be analyzed for one coal composition at ISO ambient air conditions.

Progress for this Quarter

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

The sixth Utility Advisory Board (UAB) meeting was held in May 1997. UAB members were updated on the status of ATS gas turbine performance, operability, maintainability, reliability, availability, plant arrangements, and installed costs. Several comments and questions were taken for review and discussion at the next meeting, which is planned for 4Q97.

Plans for Next Quarter

GE will continue to support the potential host utilities' technical and commercial evaluations.

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 response to a request from DOE FETC, the GE ATS Program Office led the preparation of a proposal to restructure the current ATS Phase 3 program, continuing the engineering development and component testing activities of the original Work Breakdown Structure with the addition of a catalytic combustion conceptual task and a factory full speed, no load (FSNL) test of the GE model 7H gas turbine. All other Phase 4 activities relating to the full-scale pre-commercialization testing of the Advanced Turbine System in a combined cycle power plant with a host utility were eliminated.